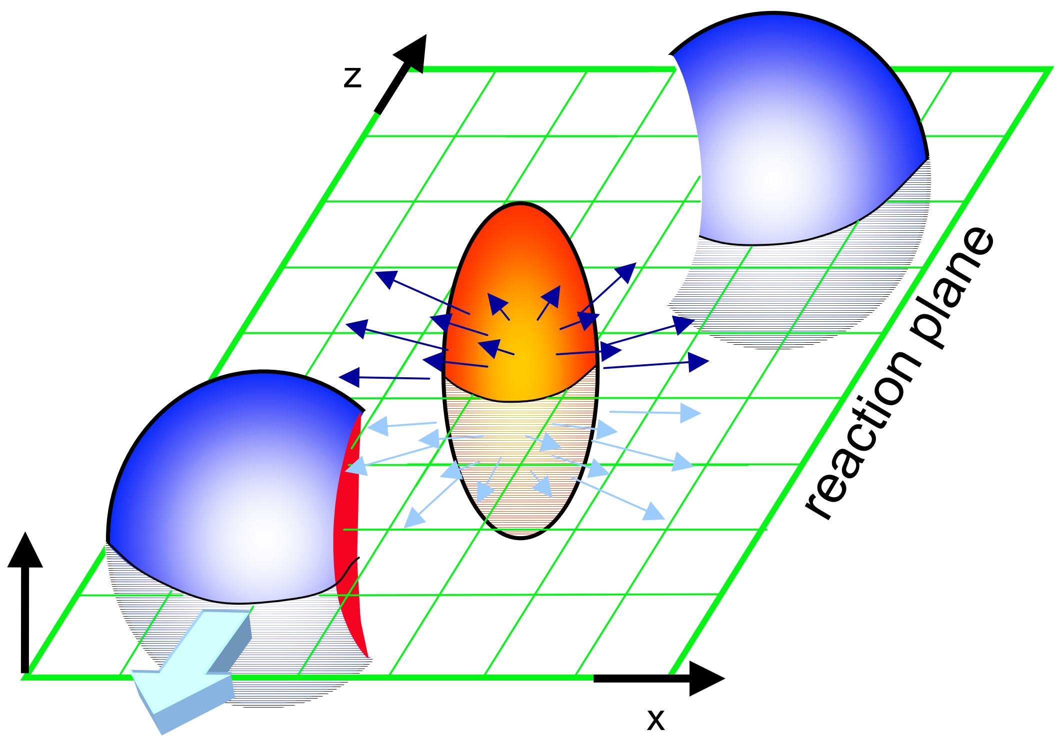
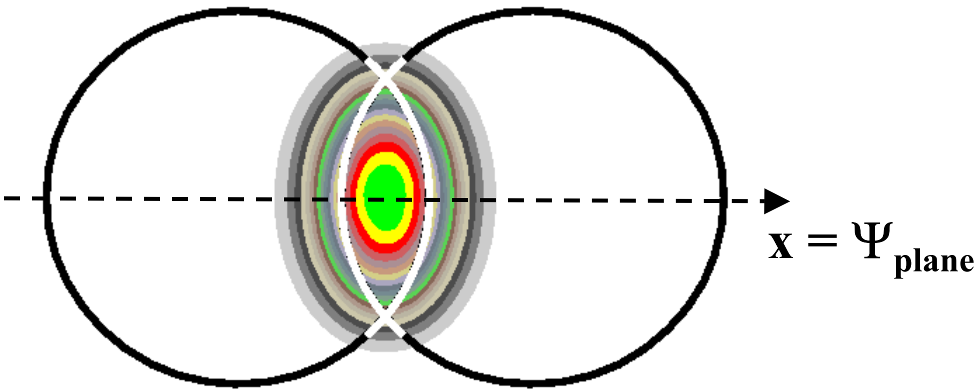
Azimuthal anisotropy

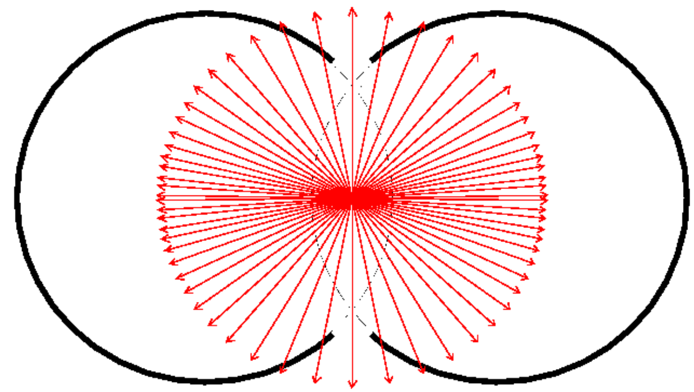


Nuclear collision is never exactly head-on-head →
→ azimuthal symmetry is broken

Hydrodynamic flow

multiple scattering → larger pressure gradient in plane → more particles emitted in plane





spatial asymmetry
eccentricity

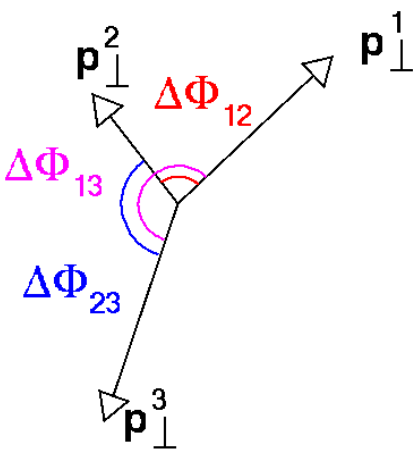
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

momentum asymmetry
elliptic flow - v2

$$v_2 = \frac{\langle p_x^{\;2} - p_y^{\;2} \rangle}{\langle p_x^{\;2} + p_y^{\;2} \rangle}$$

Sensitive to early pressure and dynamics of initial system

Two-Particles Correlation Function



Fourier decomposition

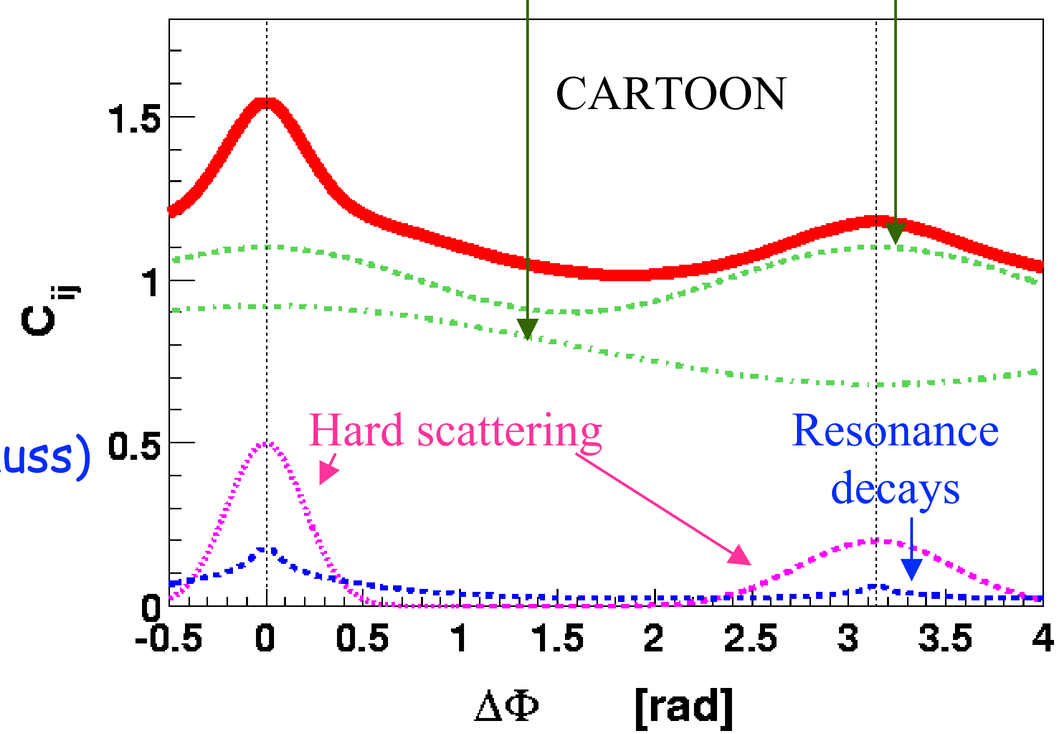
Directed flow | Elliptic flow

$$C(\Delta\phi)_{\text{flow}} \propto (1 + \boxed{2\,v_1^2 \cos(\Delta\phi)} + \boxed{2\,v_2^2 \cos(2\,\Delta\phi)})$$

$$C_{ij}(\Delta\phi) = \frac{dN_{ij}}{d(\phi_i - \phi_j)}$$

We observe a sum of

- Flow anisotropy (cos)
- Hard scattering peaks (gauss)
- Resonace decays



J.Y.Ollitrault, nucl-th/0004026

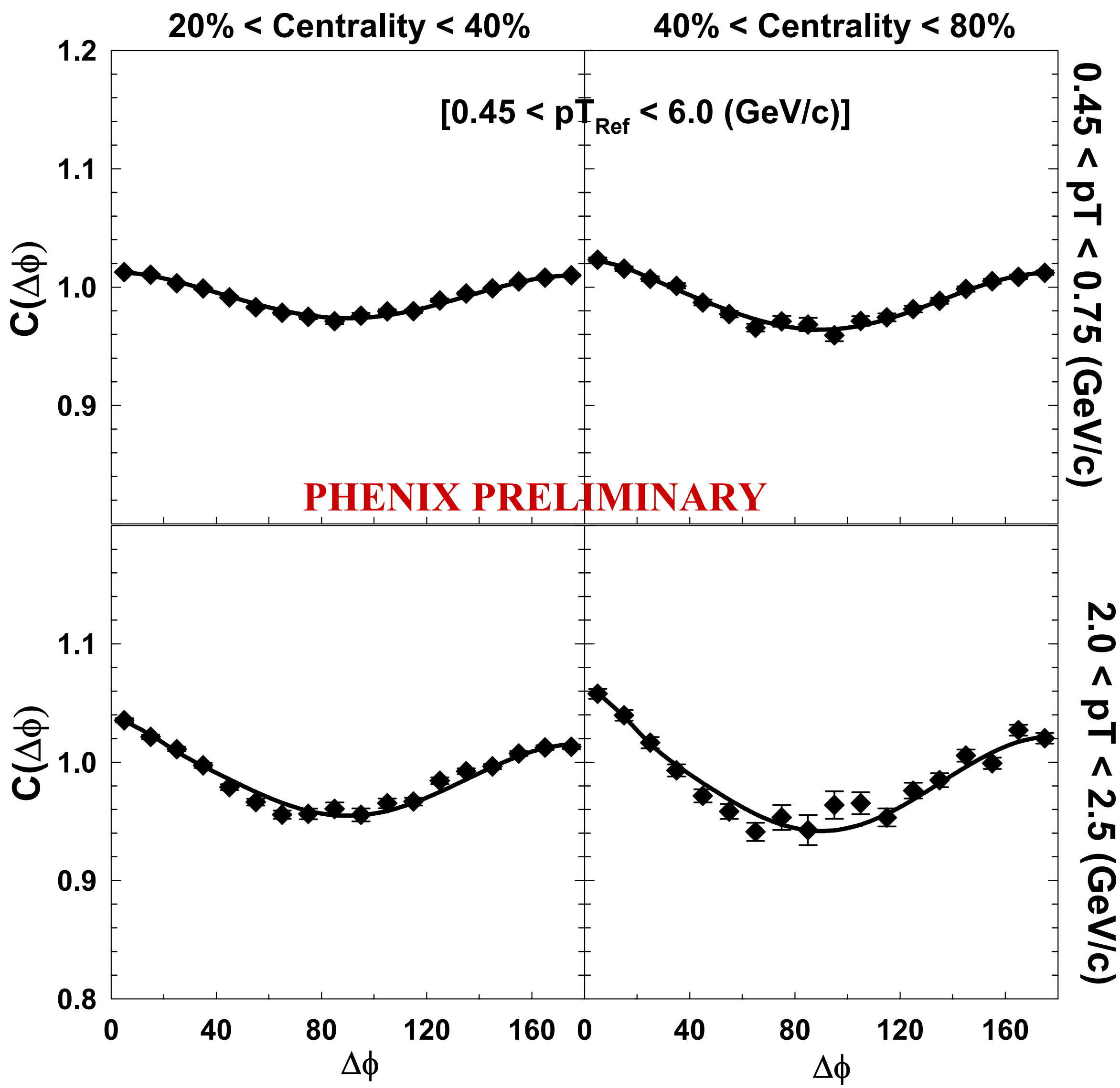
Low-pT correlation functions

$\sqrt{s_{NN}} = 200\ GeV$

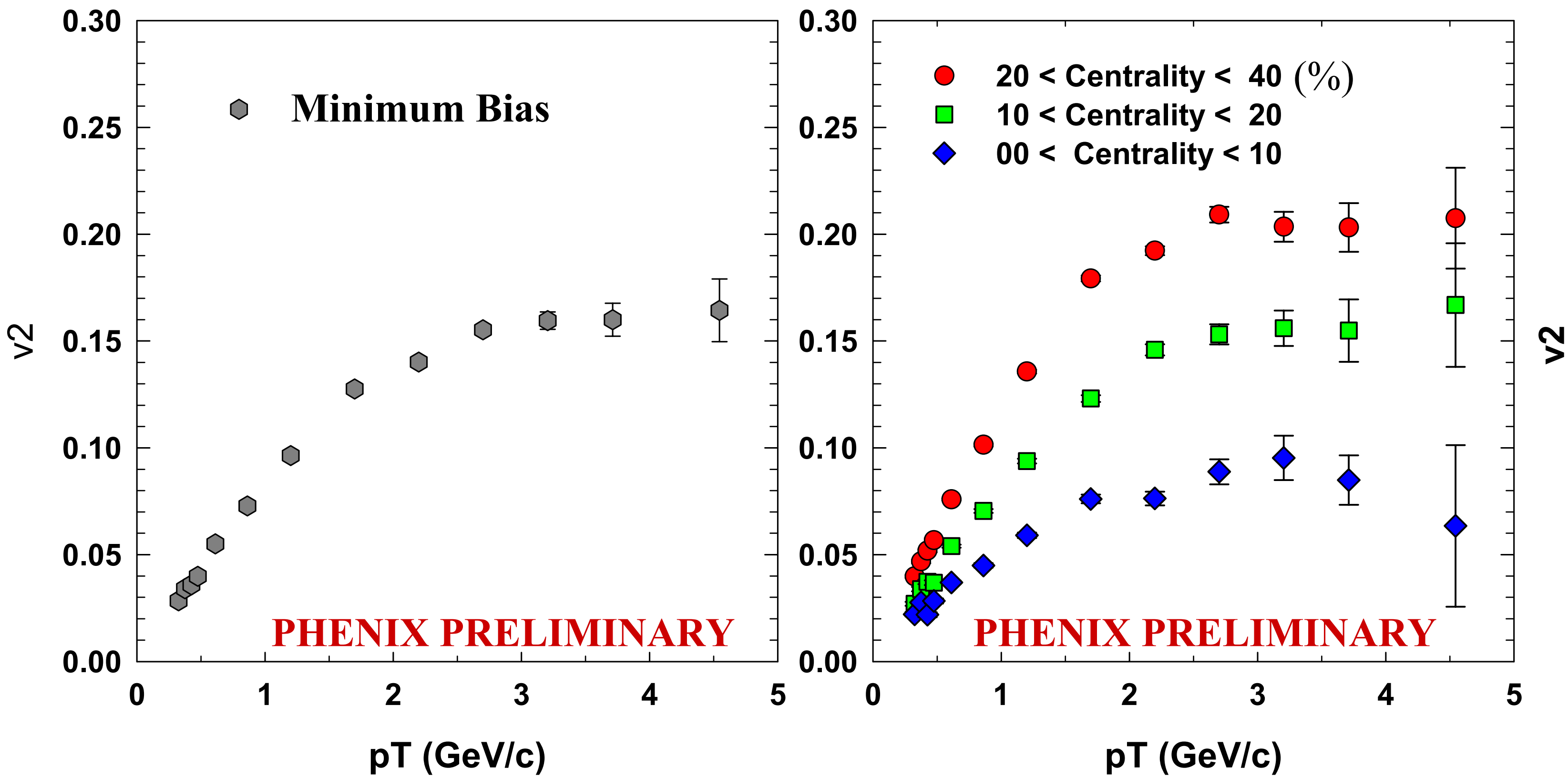
- Anisotropy increases with pt and Centrality
- Asymmetric Component seen especially at high pt

Important to test the response of the asymmetry to various Cuts

- **Jets**
- **v2 values**

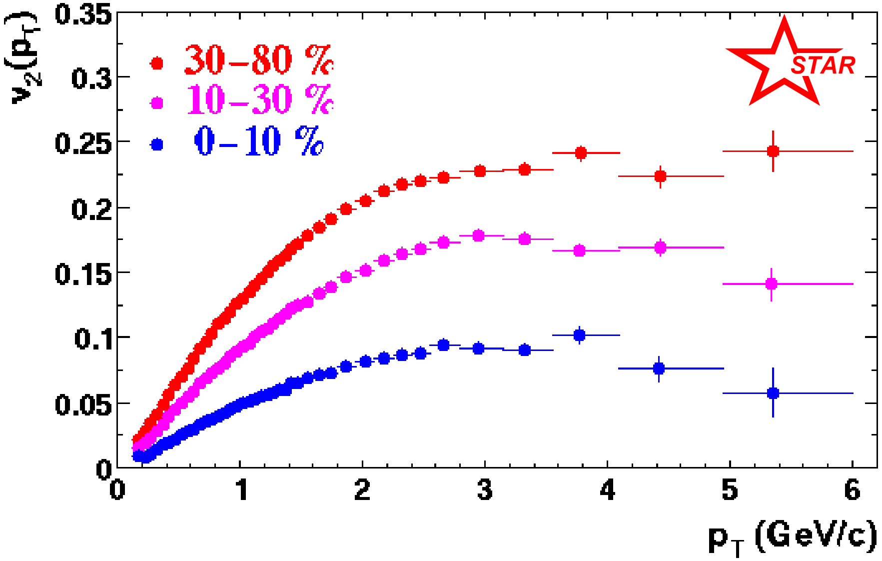


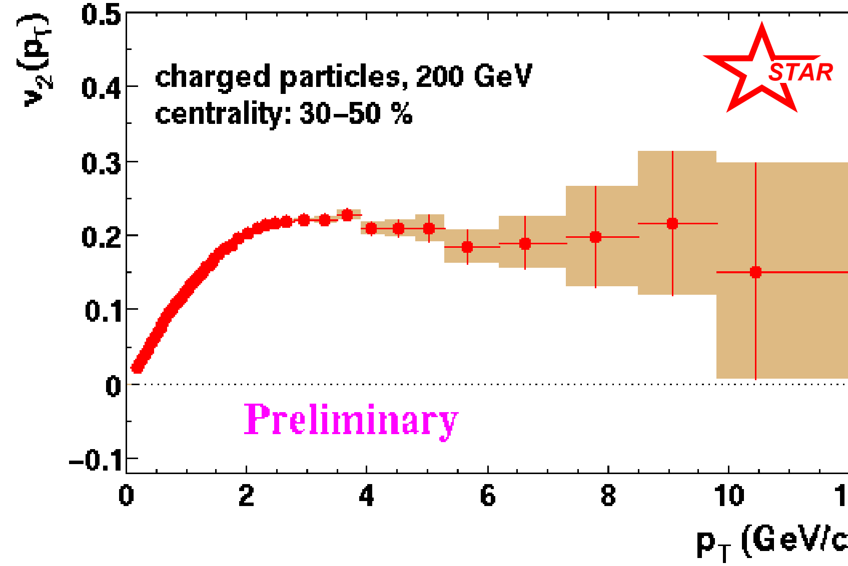
Differential v2(pT)



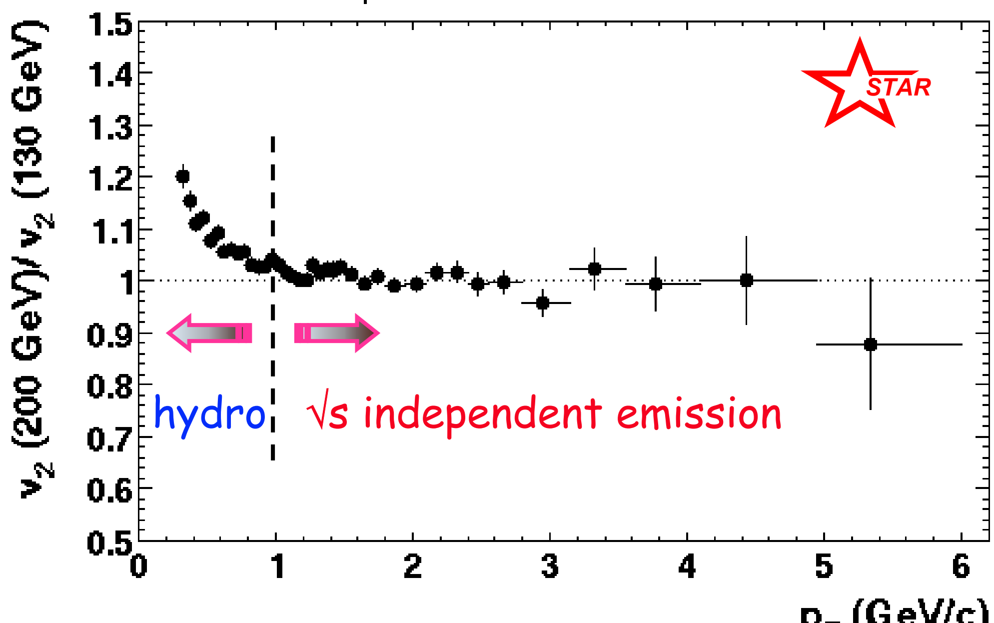
V2 Saturates at ~ 2.5 GeV/c; Similar Trend for all Centralities
V2 increases with Centrality

STAR Reaction Plane $v_2(p_T)$ $\sqrt{s}$ evolution





Excellent agreement between STAR and PHENIX

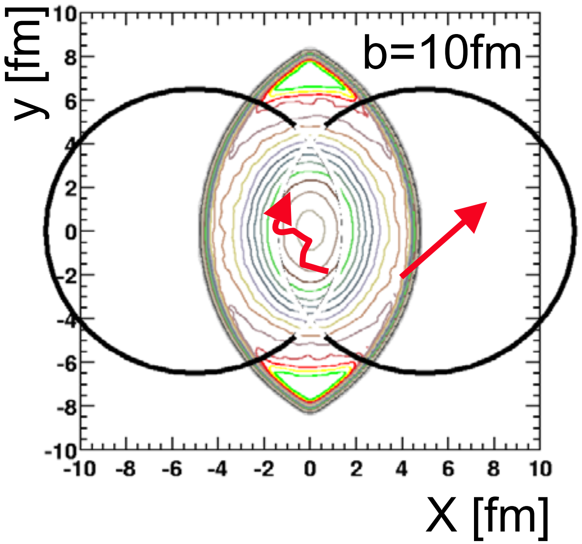


Azimuthal anisotropy

What did we learn from observed azimuthal anisotropies?

- v_2(pt) is substantial and saturates at p_T>3 GeV/c for all centralities at both beam energies
- for pt < 1GeV/c the conventional hydrodynamics seems to dominate
- for pt > 1GeV/c we observe $\sqrt{s}$ independent emission pattern.

v2 generated by energy loss of high-pT partons

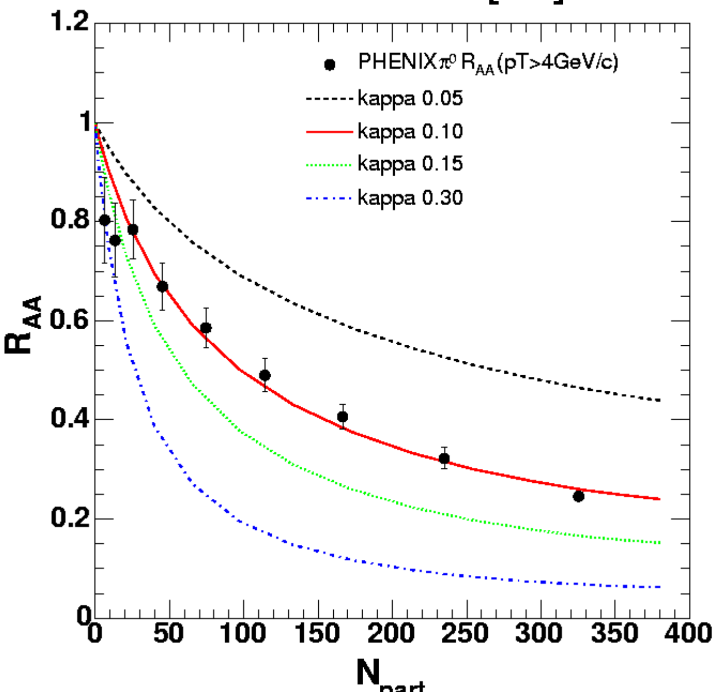


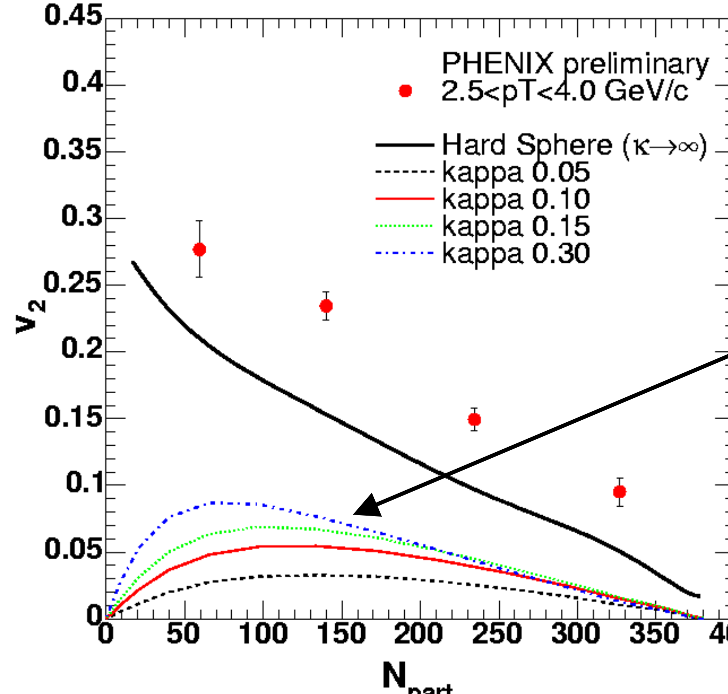
escape probability

$$f(\vec{x}_0, \vec{n}) = exp[-\kappa \int_0^\infty ds\, L_-(\vec{x}_0 + s\vec{n}) \cdot L_+(\vec{x}_0 + s\vec{n})\,].$$

$$L_\pm(x, y) = 2[R^2 - y^2 - (x \pm b/2)^2]^{1/2}$$

Or $T_A(x_0)$ thickness function with Saxon-Woods energy prof.

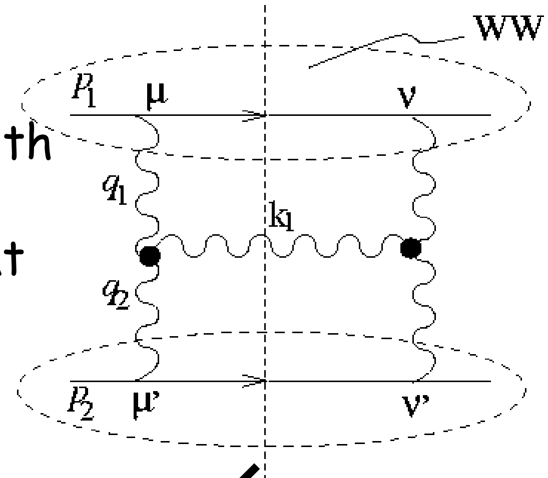


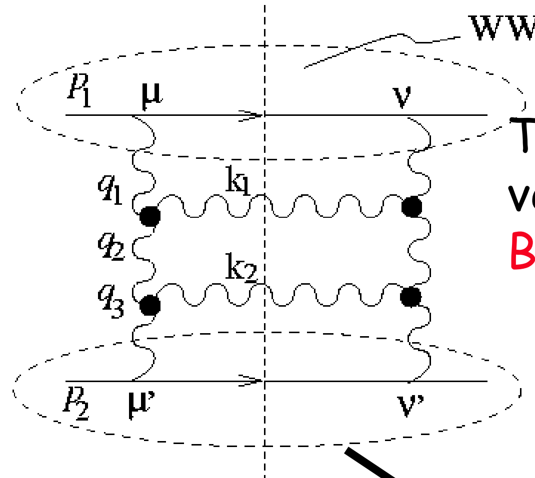


v2 generated by energy loss is way to small $v2_{max}$<10%

$v_2(p_\perp)$ from CGC

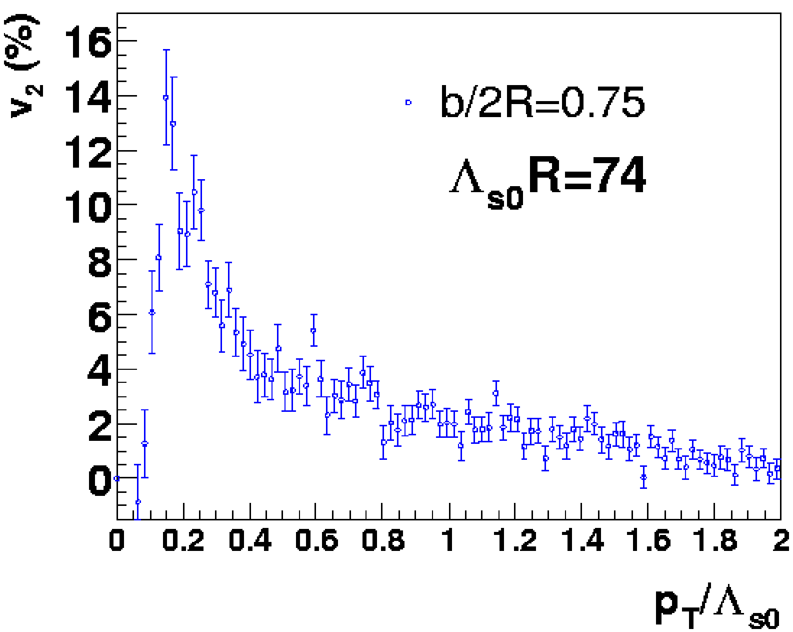
Classical CGC with mono-gluon jets doesn't get v2 at all.



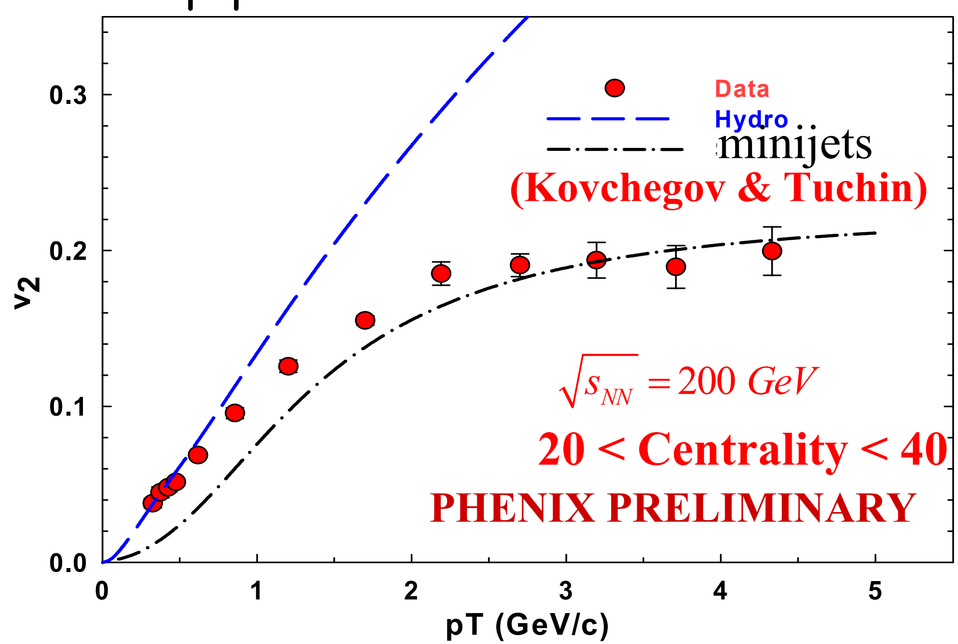


Two gluons Lipatov vertex looks OK, BUT…

hep-ph/0204361

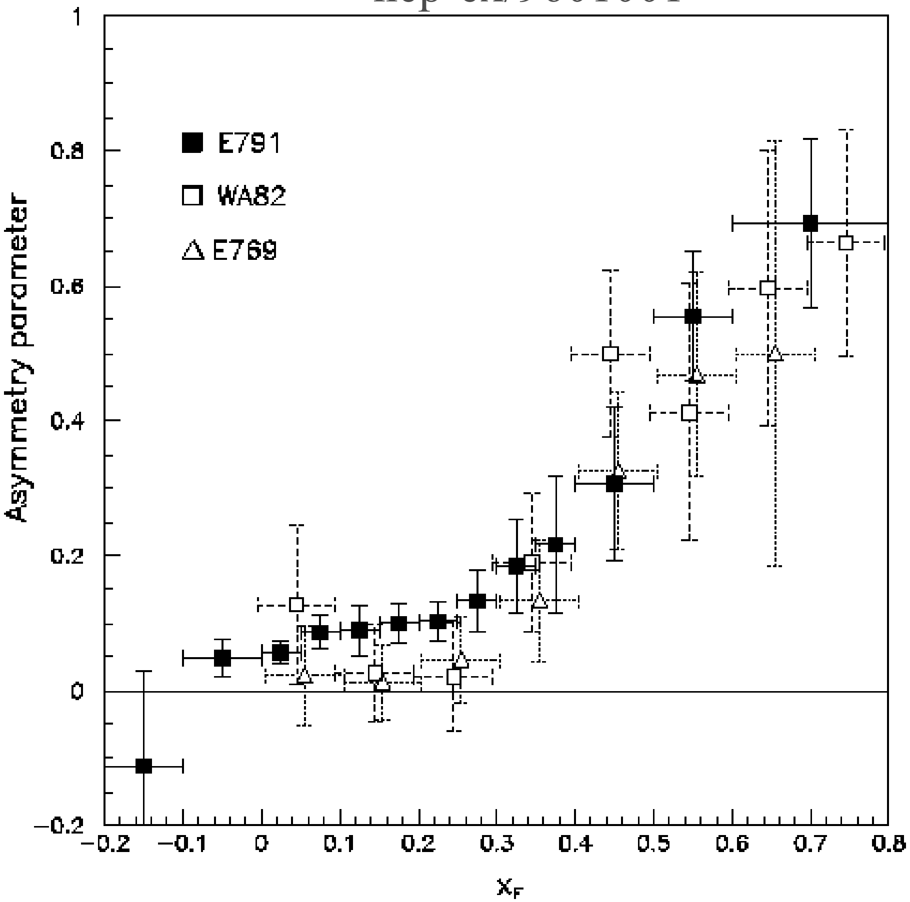


hep-ph/0203213

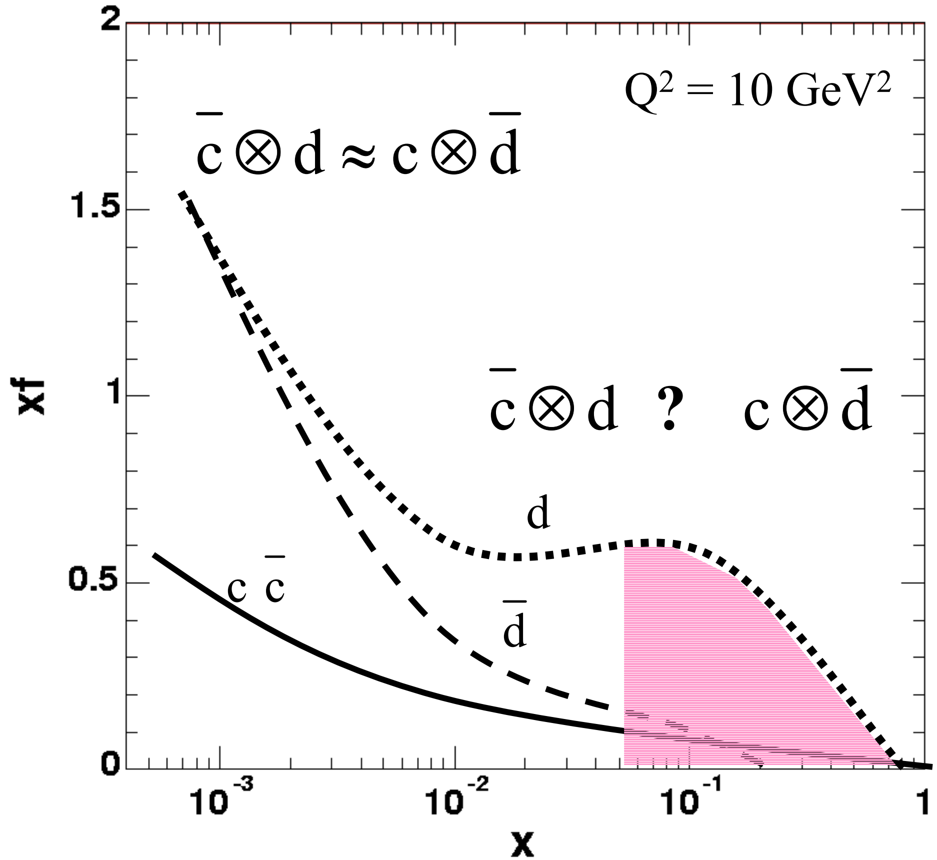


Hadron production in forward region in p+p

hep-ex/9601001



$$\alpha(x_F) = \frac{d\sigma_{D-}/dx_F - d\sigma_{D+}/dx_F}{d\sigma_{D-}/dx_F + d\sigma_{D+}/dx_F}$$

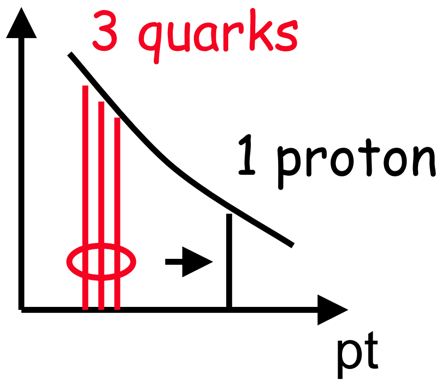


D^- from fragmentation

D^+ from coalescence and fragmentation

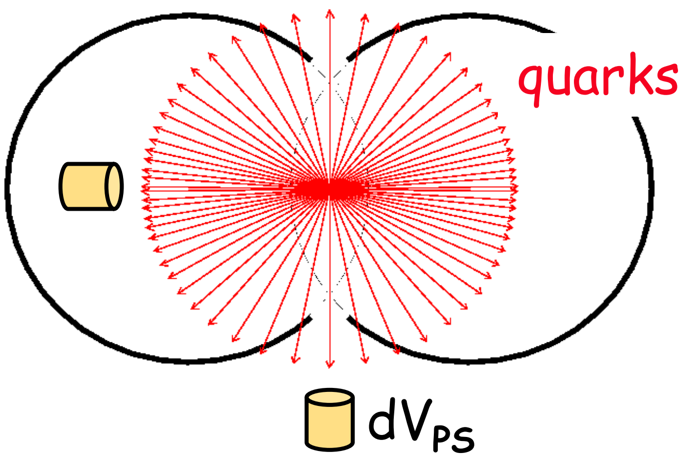
V2 amplification by quark recombination

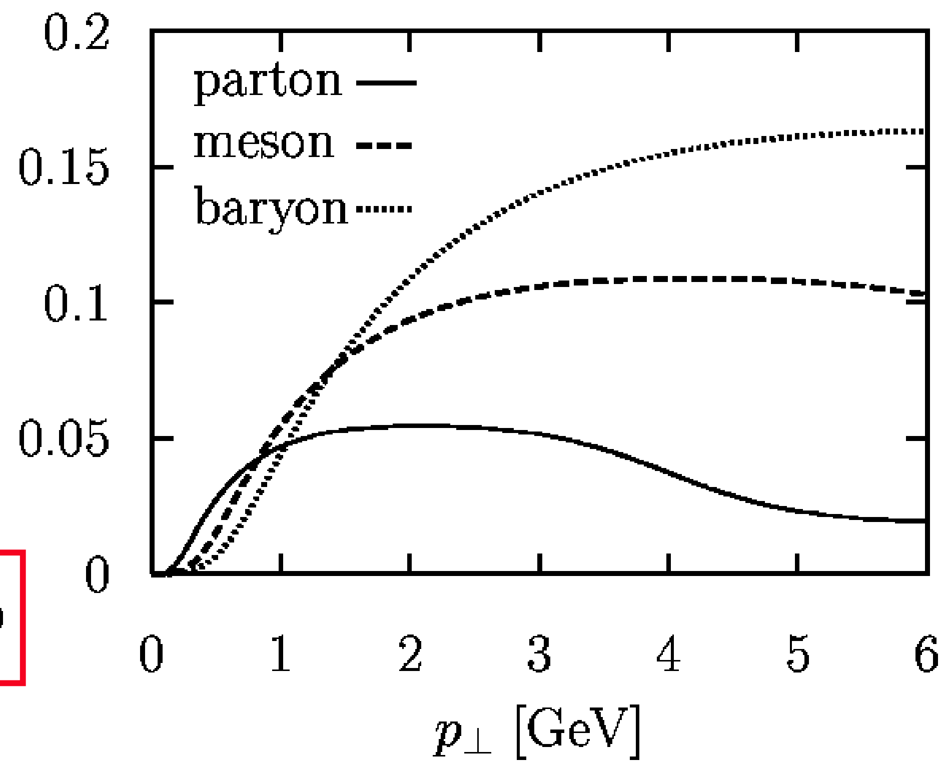
D.Molnar, S. Voloshin nucl-th/0302014



$$\frac{dN_B}{d^2p_\perp}(\vec{p}_\perp) = C_B\left[\frac{dN_q}{d^2p_\perp}(\vec{p}_\perp/3)\right]^3$$

$$\frac{dN_M}{d^2p_\perp}(\vec{p}_\perp) = C_M\left[\frac{dN_q}{d^2p_\perp}(\vec{p}_\perp/2)\right]^2$$

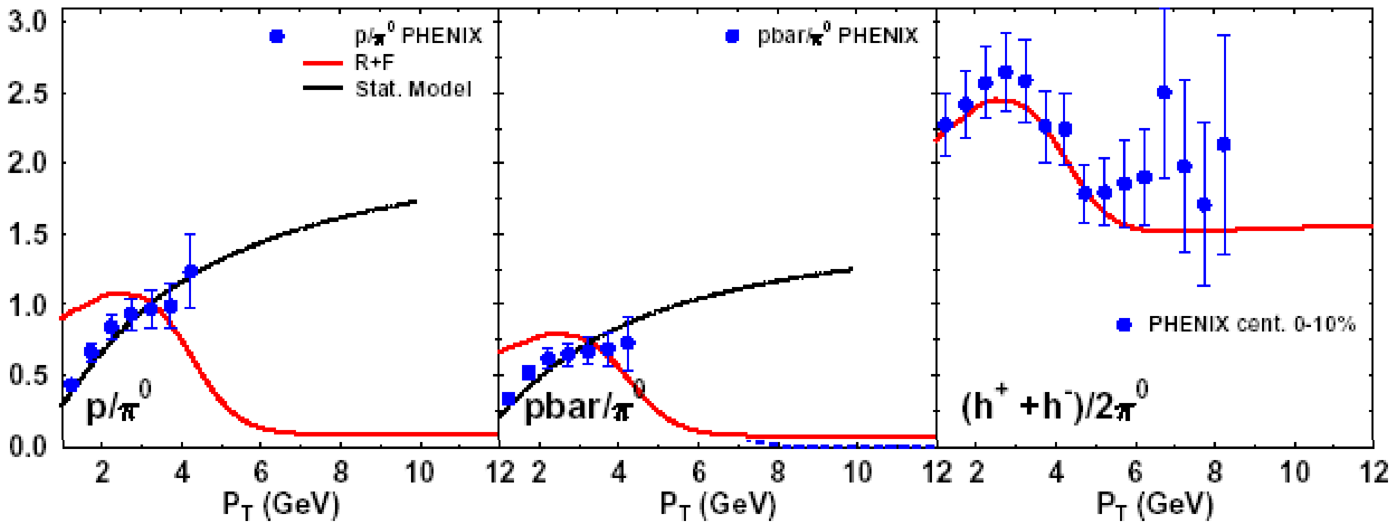


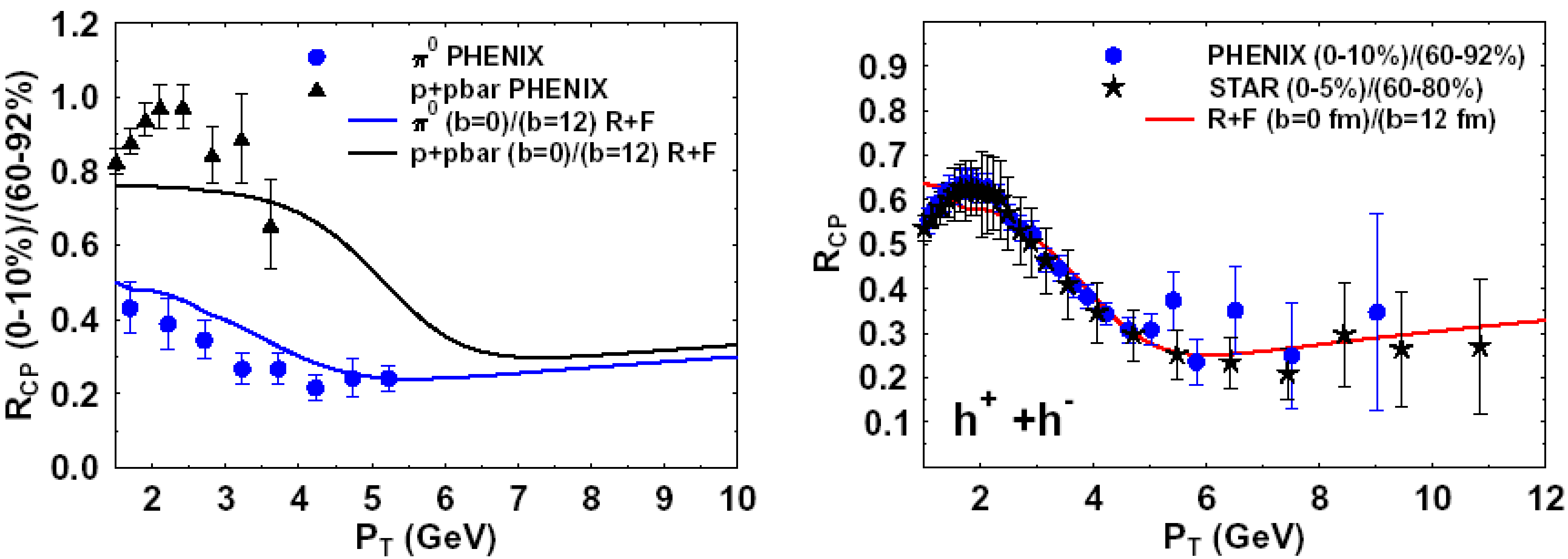


$$v_{2,M}(p_\perp) \approx 2v_{2,q}\left(\frac{p_\perp}{2}\right), \quad v_{2,B}(p_\perp) \approx 3v_{2,q}\left(\frac{p_\perp}{3}\right)$$

Hall of fame

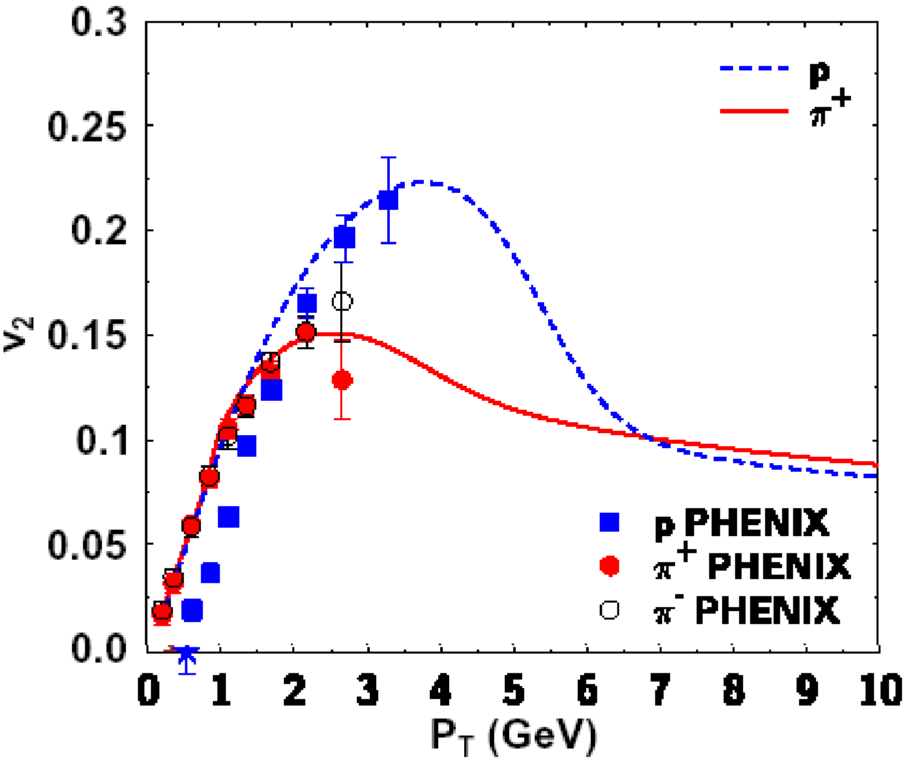
nucl-th/0306027 v2 **5 Jun 2003** ***"Hadron production in heavy ion collisions: Fragmentation and recombination from a dense parton phase"*** **R. J. Fries, B. M¨uller, and C. Nonaka S. A. Bass**



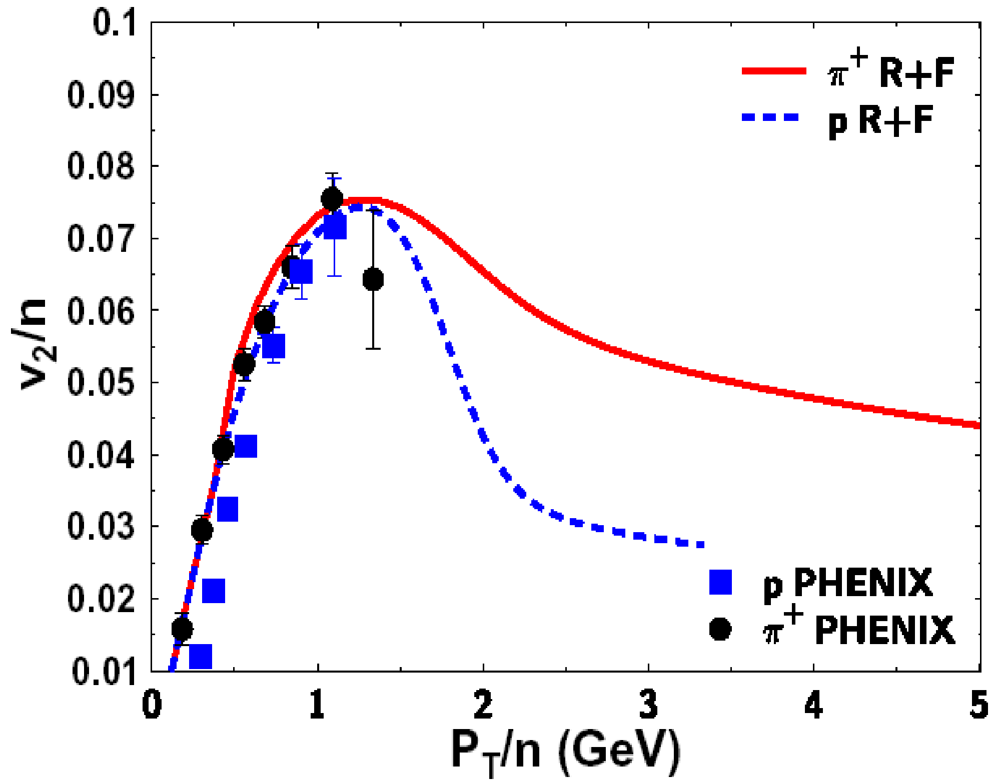


Hall of fame II

v2 for p and charged π

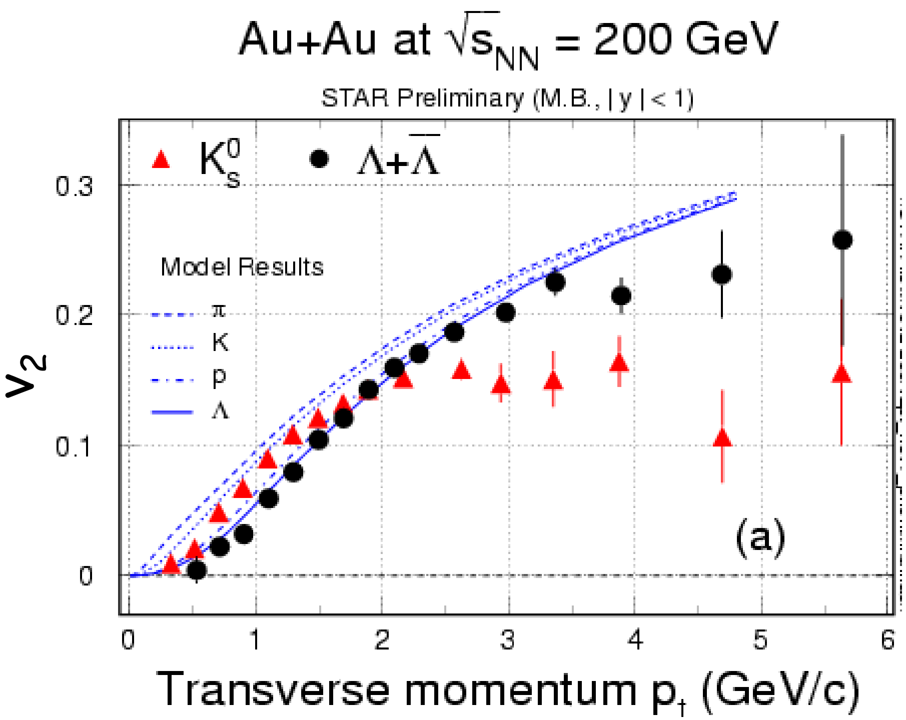


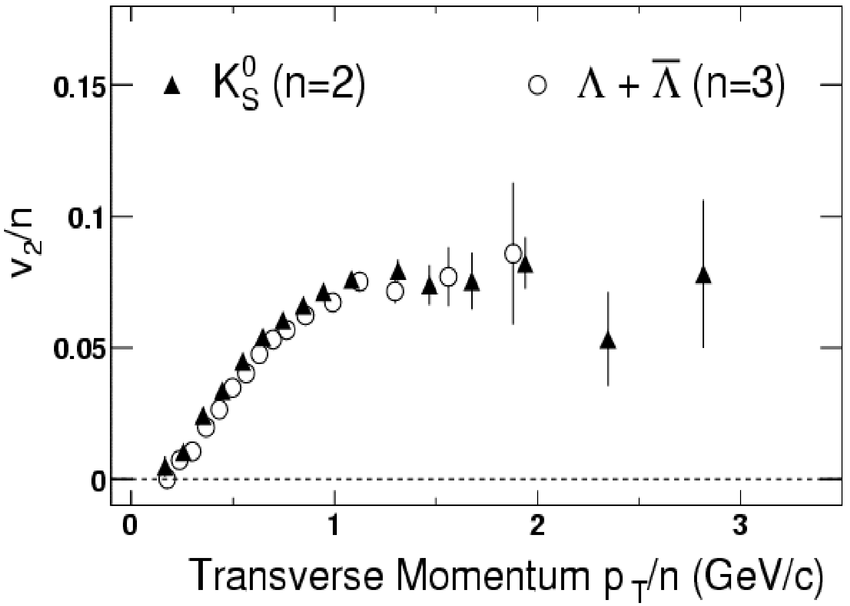
v2 for p and charged π scaled by quantum #



Beautiful ! We might see the partonic flow!

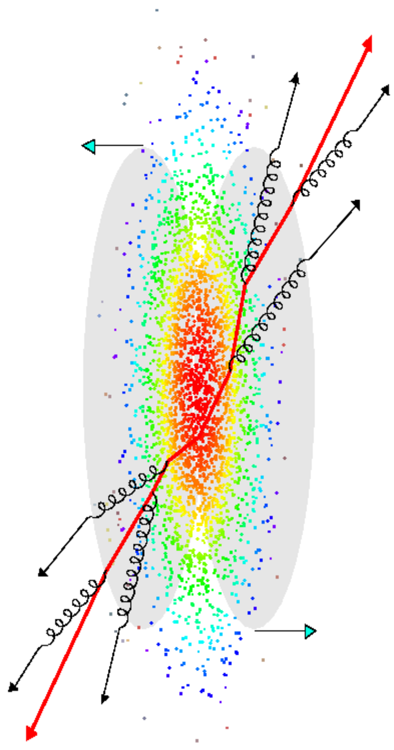
STAR strange mesons and baryons scaling





Hard scattering in Heavy Ion collisions

schematic view of jet production



Particle production @RHIC

- $dn_{ch}/d\eta\,|_{\eta=0} = 670$, $N_{total} \sim 7500$
  92% of (15,000) all quarks
  from vacuum !

Jets @RHIC:

- produced early τ<1fm
- primarily from gluons
- 30-50% of particle production

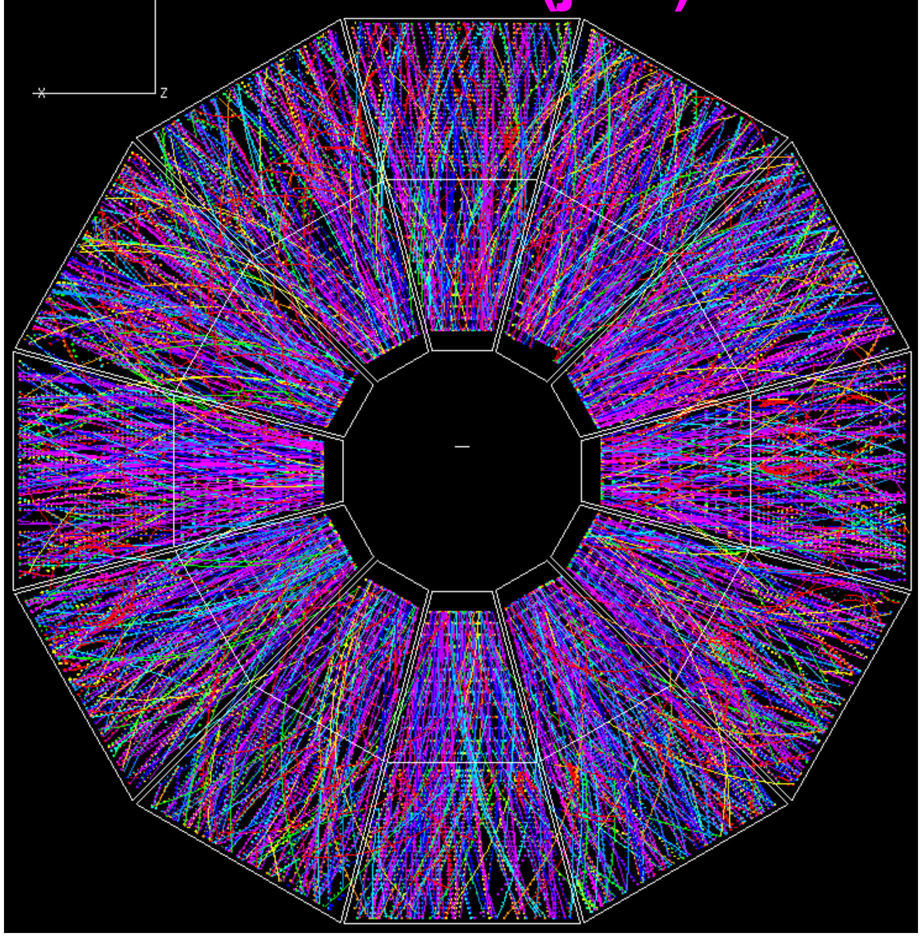
Observed via:

- fast leading particles
- azimuthal correlations

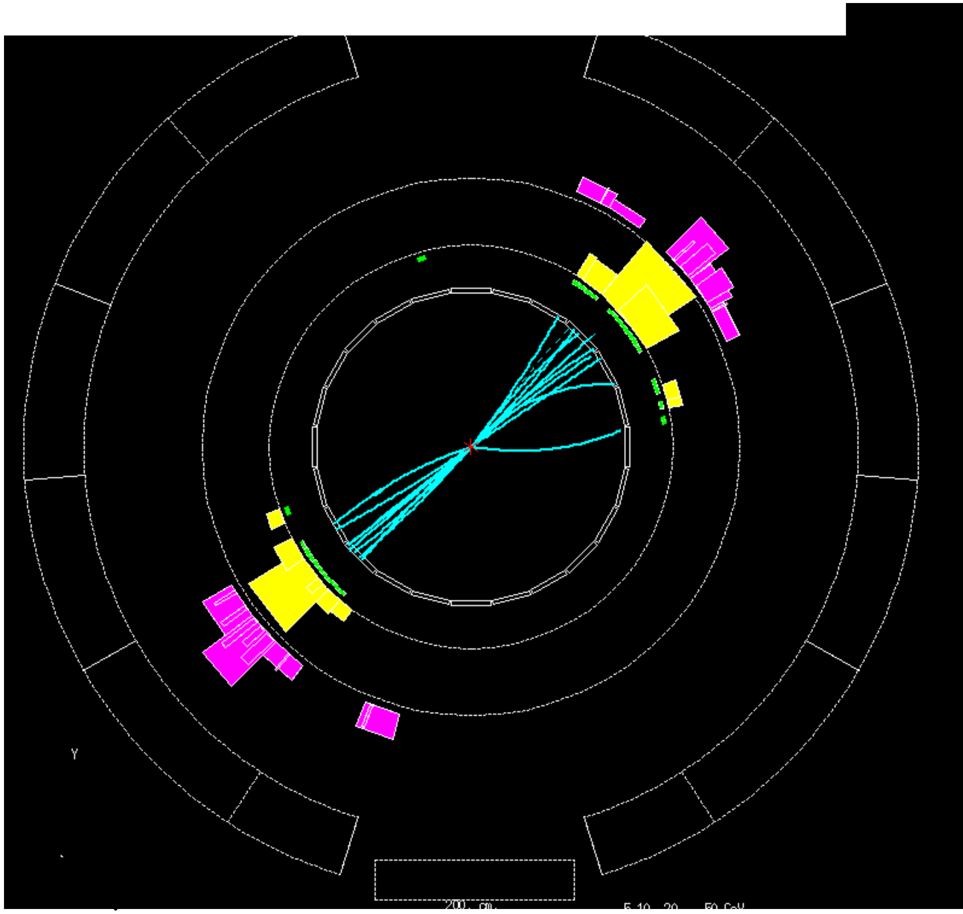
Scattered partons radiate energy in colored medium →
suppression of high p_t particles

Hard Scattering (Jets) as a Probe of Dense Matter

STAR Au+Au (jet?) event



Jet event in e^+e^- collision



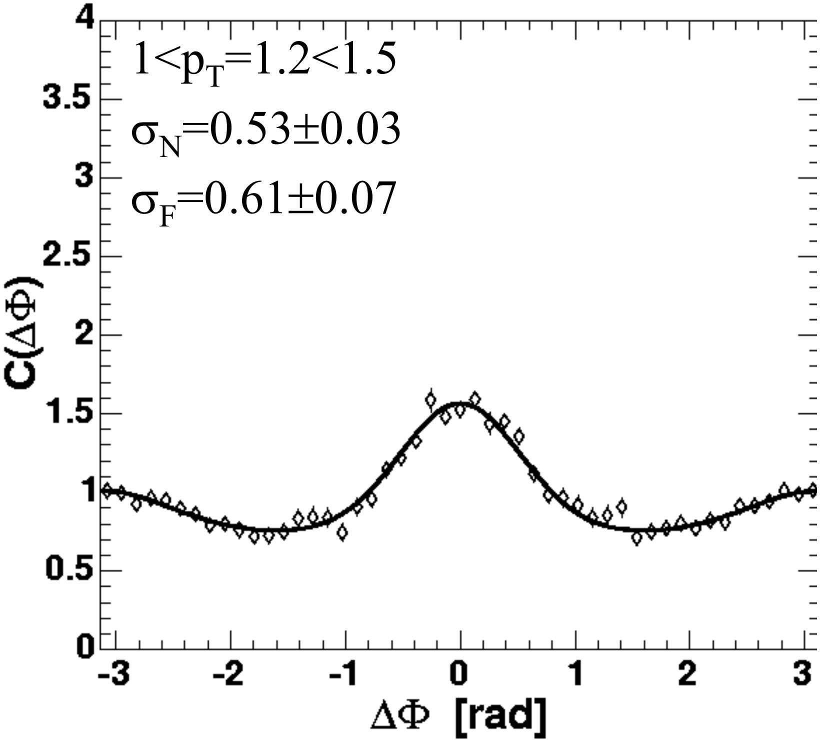
Can we see jets in high energy Au+Au?

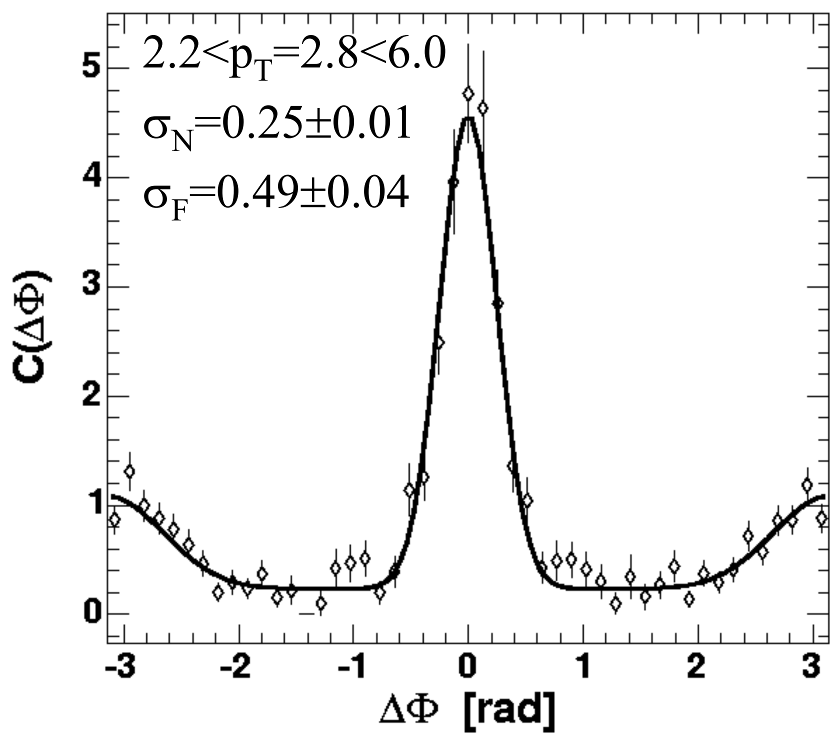
Two-particles correlation in pp

pp correlation function, even at intermediate p_T range, dominated by jet fragments.

The near angle peak width σ_N intra-jet correlations

The far angle peak width σ_F inter-jet correlations

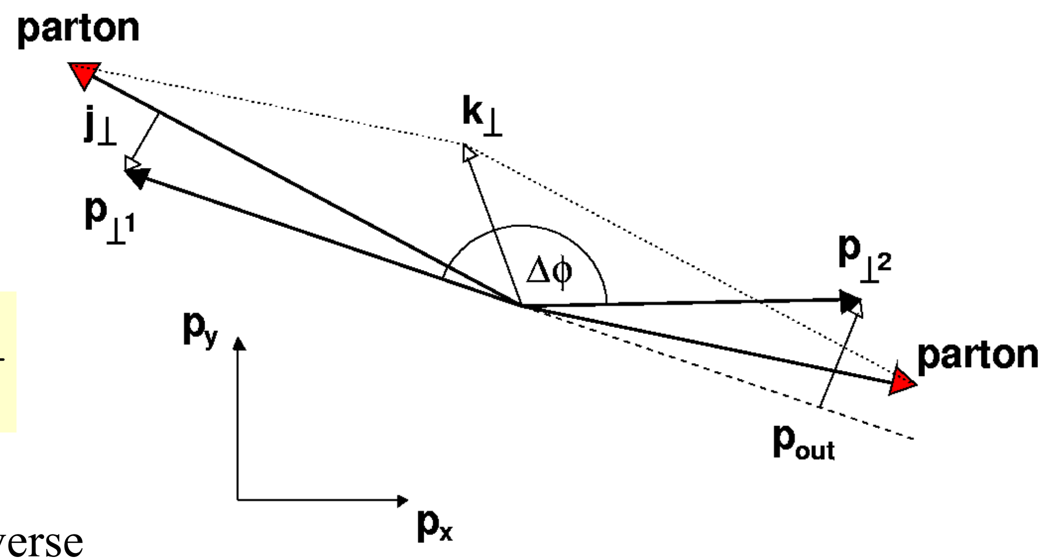




Fit = const + Gauss(0)+Gauss(±π)

jet fragmentation transverse momentum

$\langle|j_{\perp y}|\rangle$ = the mean transverse momentum of the hadron with respect to the jet axis.



$$\left\langle\left|j_{\perp y}\right|\right\rangle = \frac{1}{\sqrt{\pi}}\sqrt{\left\langle j_\perp^2\right\rangle} = \left\langle p_\perp\right\rangle \sin\frac{\sigma_N}{\sqrt{\pi}}$$

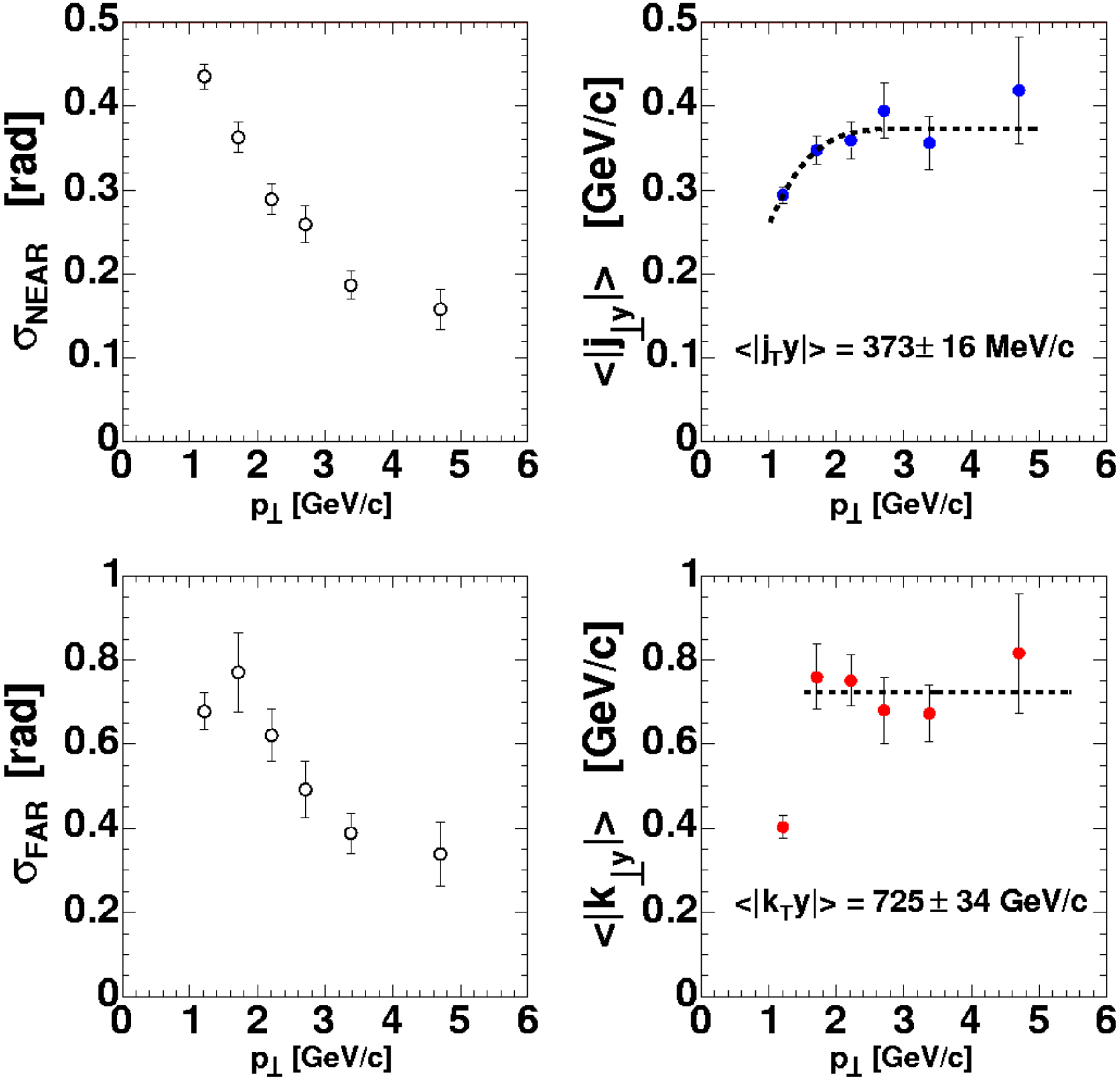
$\langle|k_{\perp y}|\rangle$ = the mean effective (net) transverse momentum of the two colliding partons.

$$\left\langle\left|k_{\perp y}\right|\right\rangle = \frac{1}{\sqrt{\pi}}\sqrt{\left\langle k_\perp^2\right\rangle} = \left\langle p_\perp\right\rangle \cos\left(\frac{\sigma_N}{\sqrt{\pi}}\right)\sqrt{\frac{1}{2}\tan^2\left(\sqrt{\frac{2}{\pi}}\sigma_F\right) - \tan^2\left(\frac{\sigma_N}{\sqrt{\pi}}\right)}$$

$$\boxed{\left\langle k_\perp^2\right\rangle_{AA} = \left\langle k_\perp^2\right\rangle_{vac} + \left\langle k_\perp^2\right\rangle_{IS\ nucl} + \left\langle k_\perp^2\right\rangle_{FS\ nucl}}$$

charged hadrons correlation in pp $\sqrt{s}$ = 200GeV

No systematic errors shown



At low p_T<2GeV the near angle peak width and $\langle|j_{Ty}|\rangle$ is reduced by "Seagull effect"

see. e.g **Phys.Lett.B320:411-416,1994**

pp reference

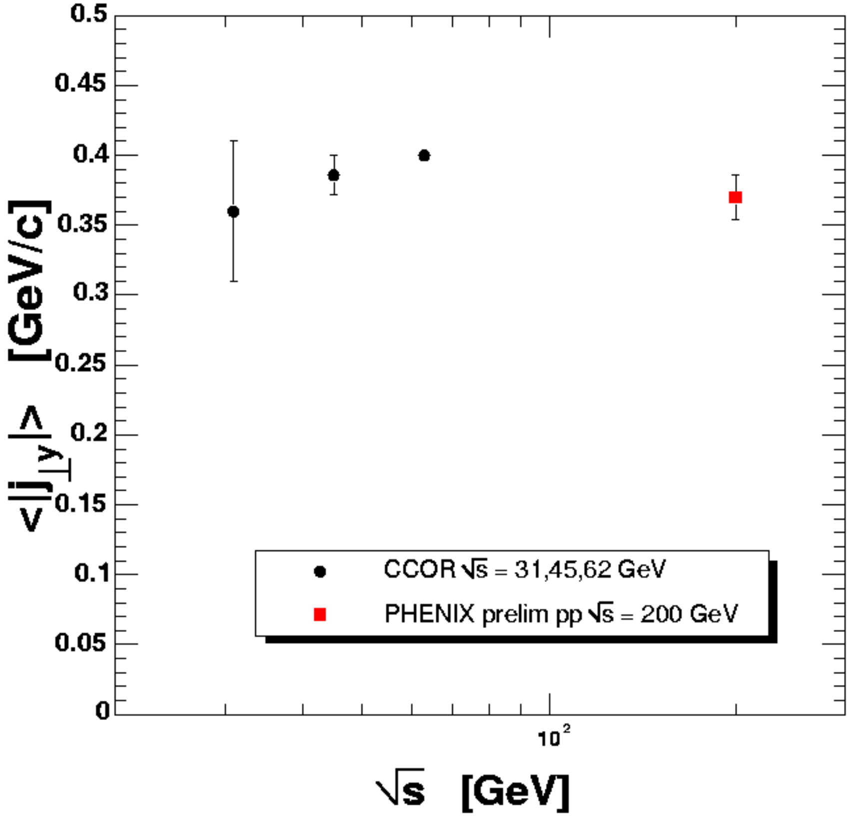
PHENIX preliminary

$\langle|j_{Ty}|\rangle$ = 373±16 MeV/c

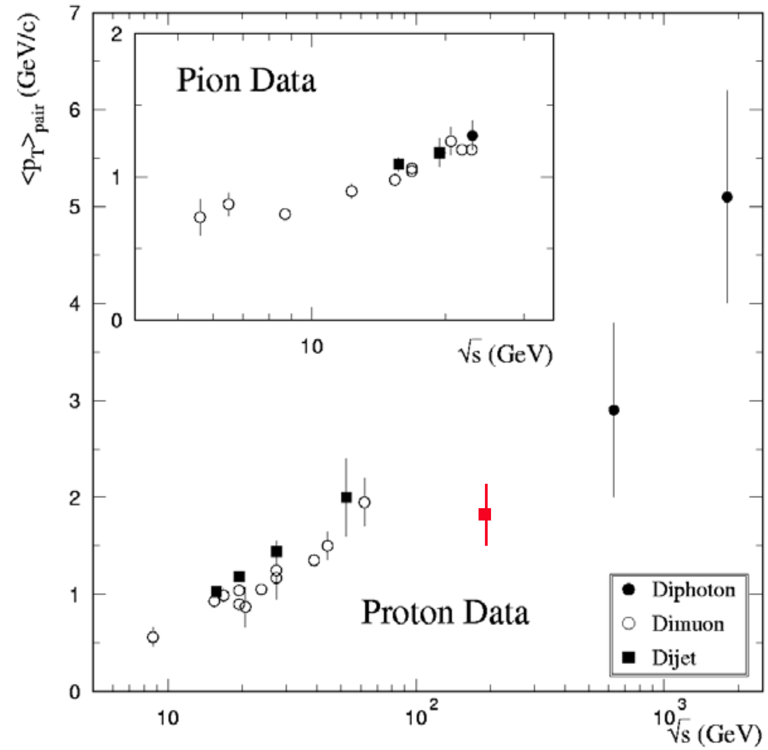
$\langle|k_{Ty}|\rangle$ = 725±34 MeV/c

P0 fit to data above 1.5 GeV/c

Comparison with $\bar{p}p$



CCOR Collaboration
Phys. Lett. 97B(1980)163

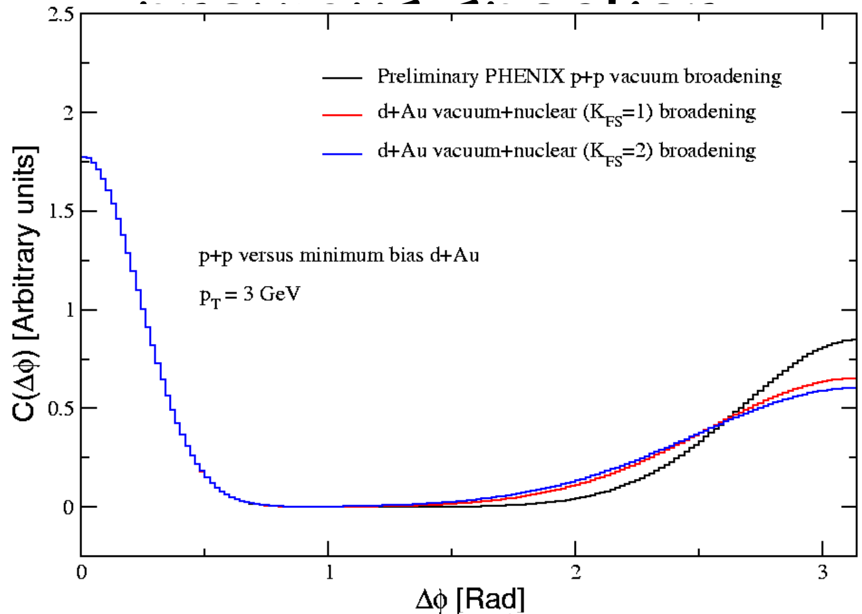


Compilation of $\langle p_\perp \rangle_{pair}$ results:
Apanasevich et al
Phys. Rev. D59(1999)074007

$$\sqrt{\left\langle \mathbf{p}_\perp{}^2 \right\rangle_{\mathbf{pair}}} = \sqrt{\mathbf{2}}\sqrt{\left\langle \mathbf{k}_\perp{}^2 \right\rangle} = \sqrt{\mathbf{2\pi}}\left\langle \left| \mathbf{k}_{\perp \mathbf{y}} \right| \right\rangle$$

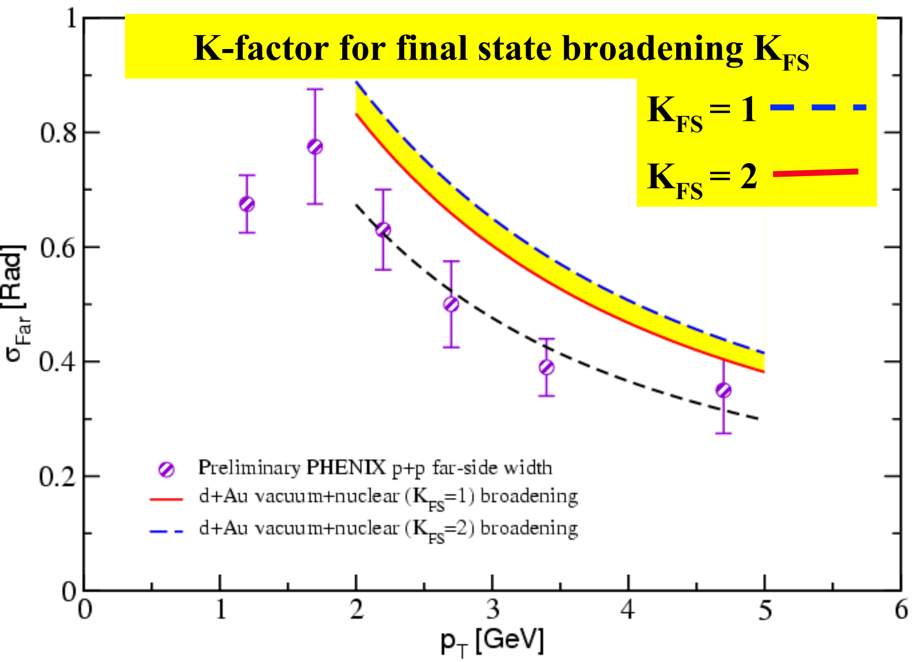
Initial/final (cold) state broadening -

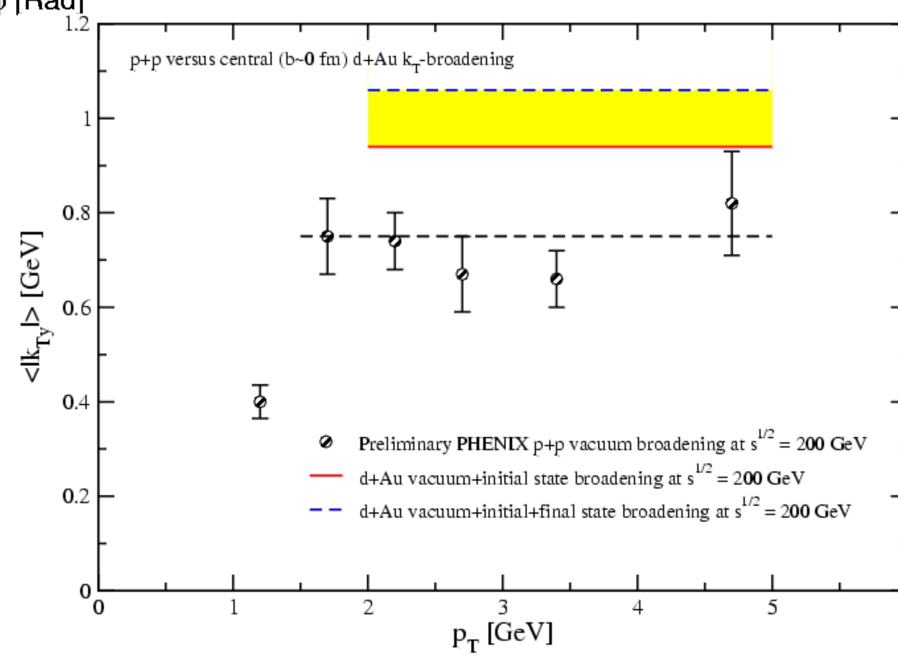
If the fragmentation occurs only outside QCD medium - σ_N remain unchanged by induced gluon radiation



Both initial and final state interactions lead to enlargement of σ_F observed as

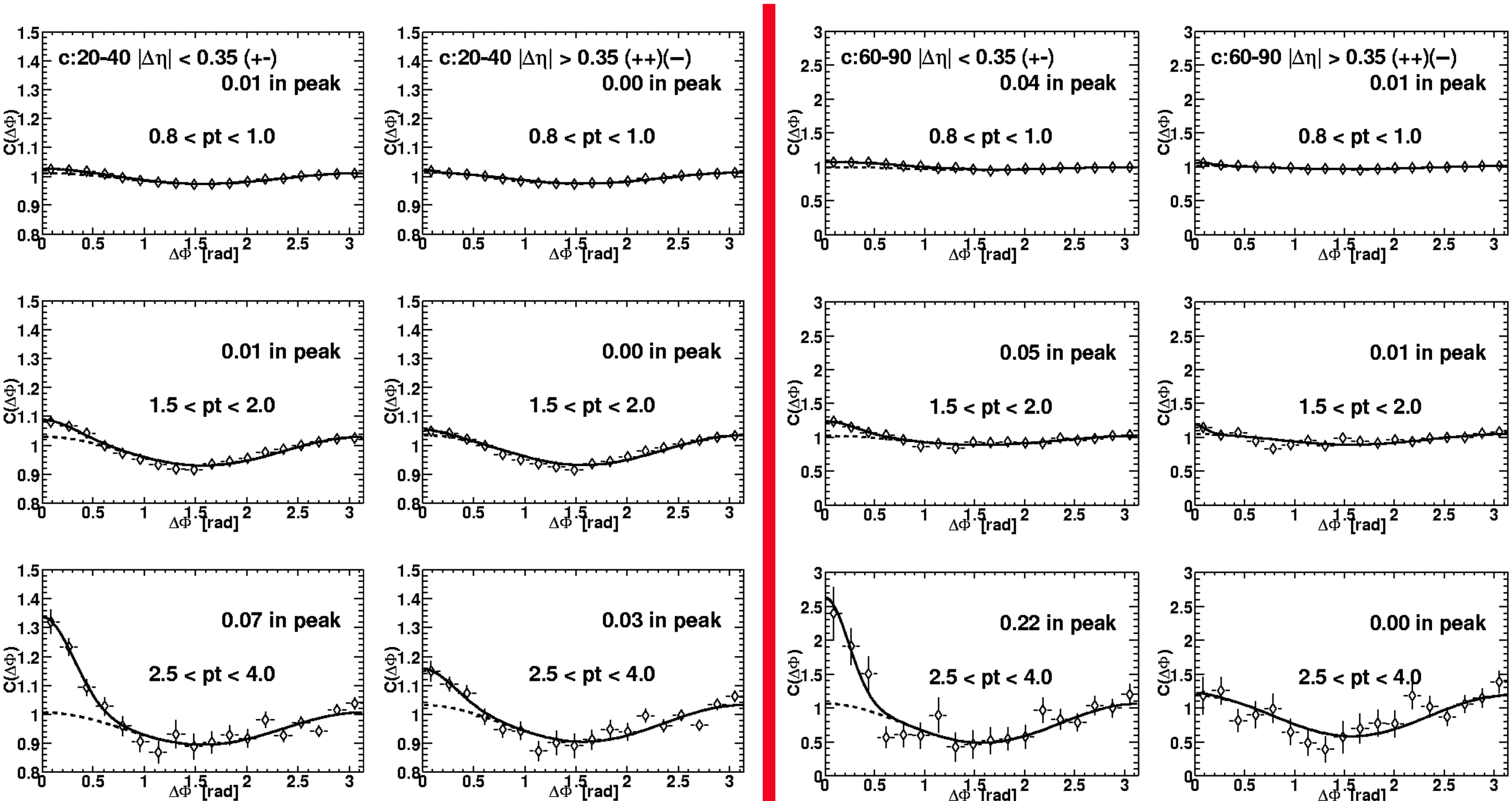
$\langle k_T \rangle$ -broadening





Jet-cone correlations

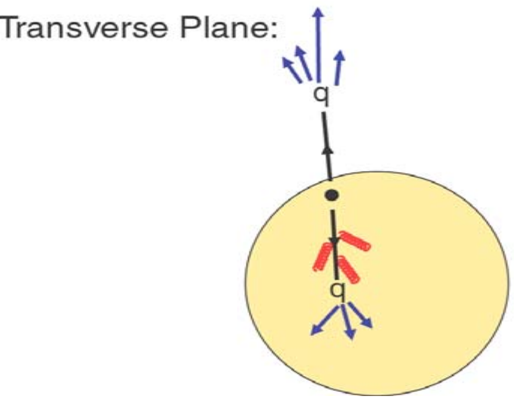
One of the most direct way of jet detection in AA high-multiplicity environment is a method based on two-particle correlations.

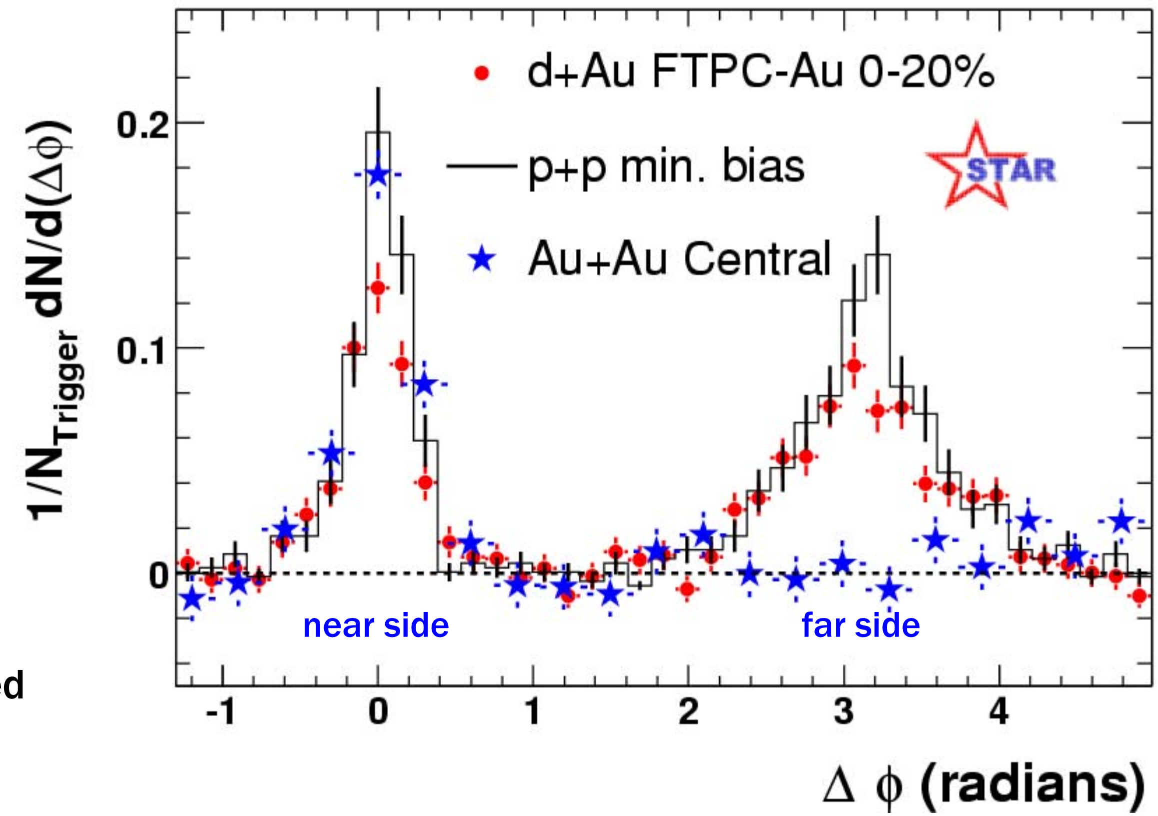


central peripheral

- Jet Correlation (STAR Collaboration) -

$\sqrt{s_{NN}} = 200$ GeV

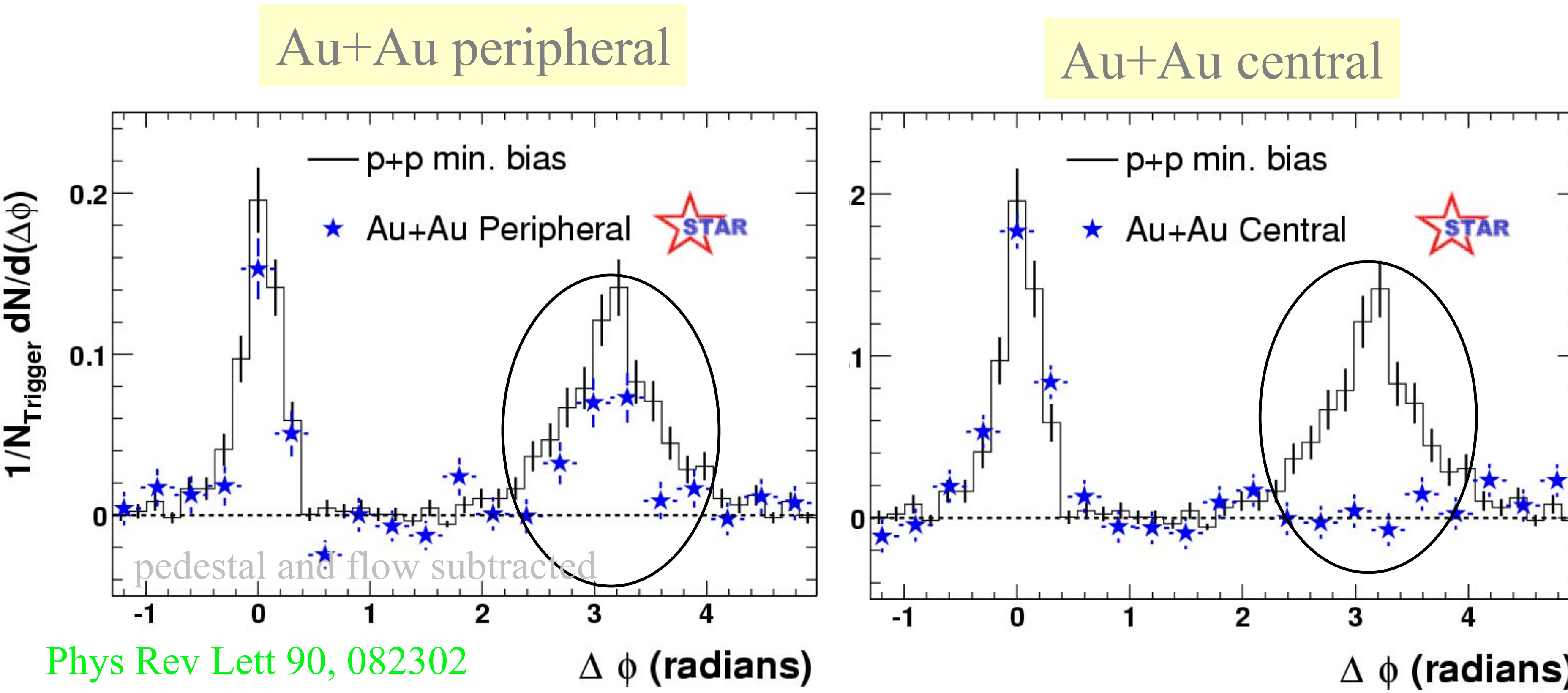




pedestal and flow subtracted

- **back-to-back correlation suppressed in central Au+Au**

Azimuthal distributions in Au+Au

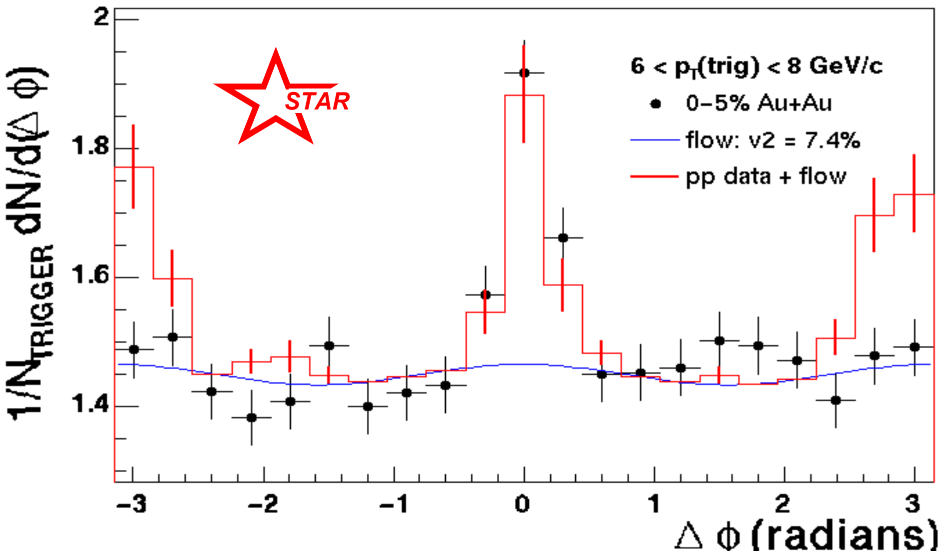


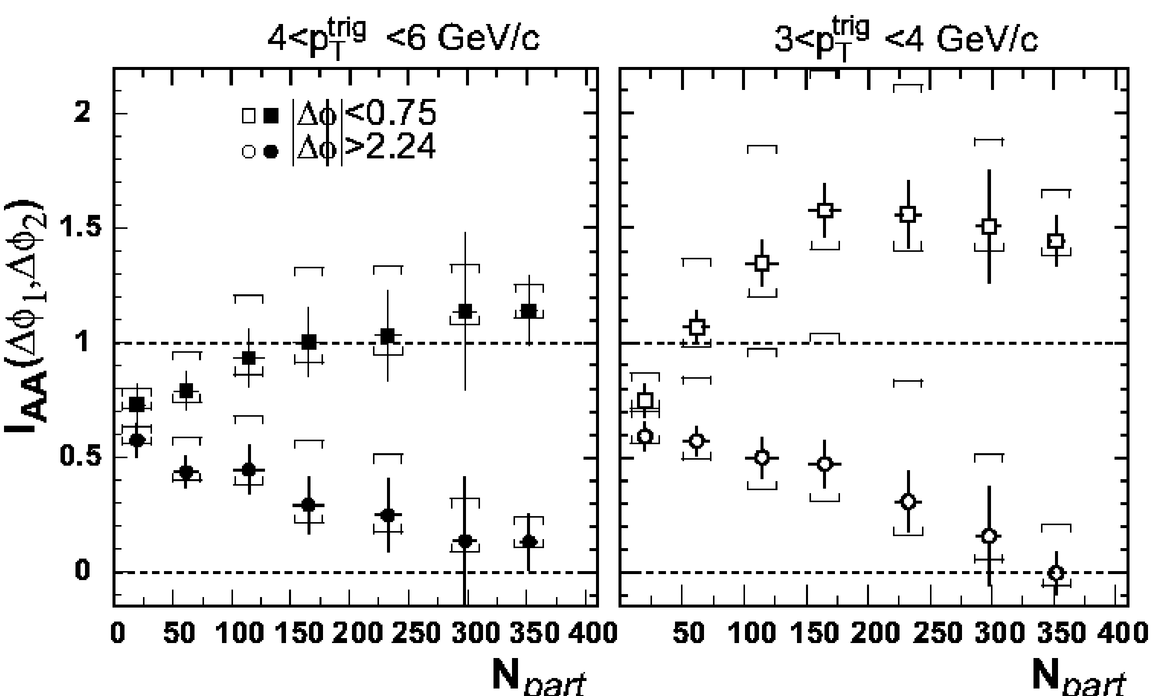
Phys Rev Lett 90, 082302

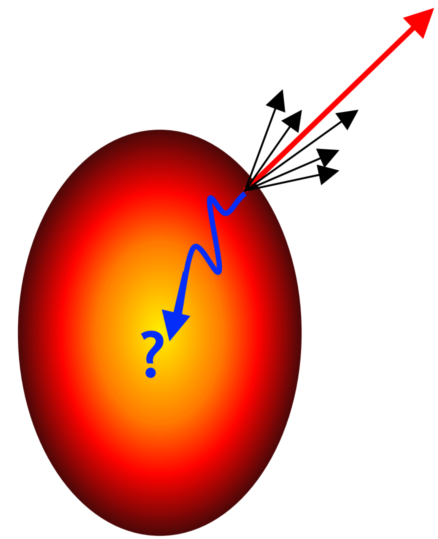
Near-side: peripheral and central Au+Au similar to p+p

Strong suppression of back-to-back correlations in central Au+Au

STAR jets and away-side quenching





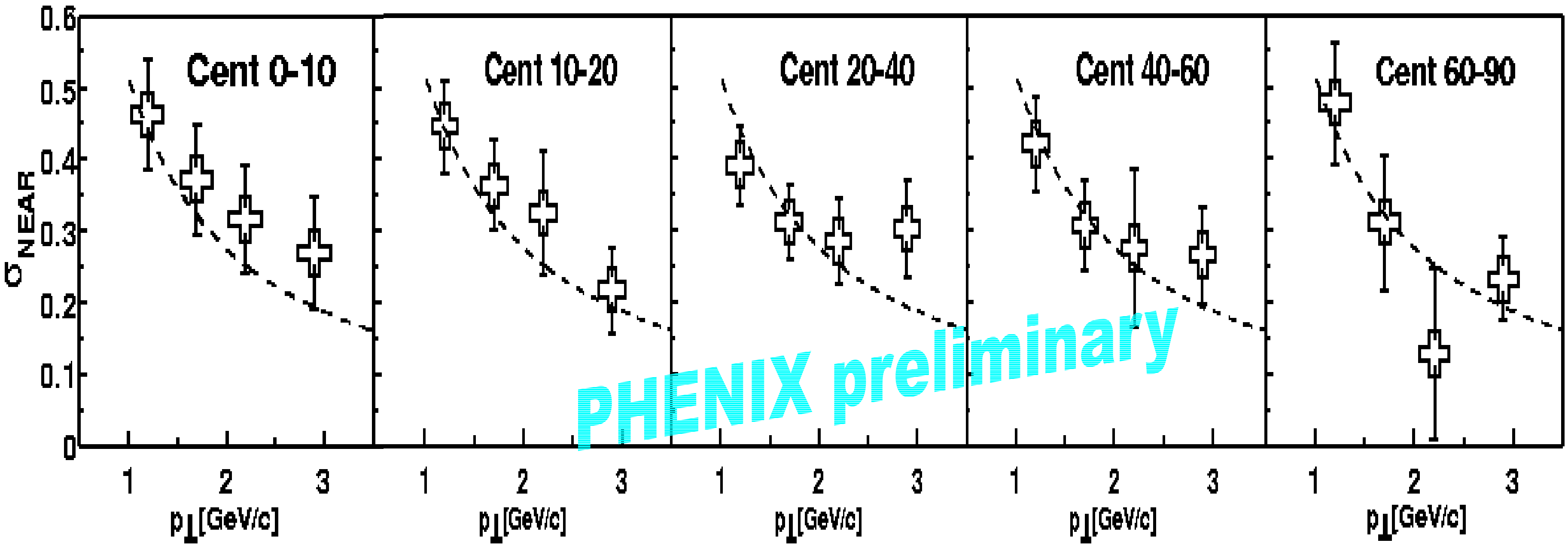


Hint of surface emission ?

Nucl-ex/0210033

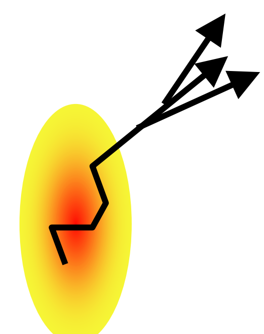
Near angle peak width in AuAu

Let us do the same fit, but σ_N fitted as well.



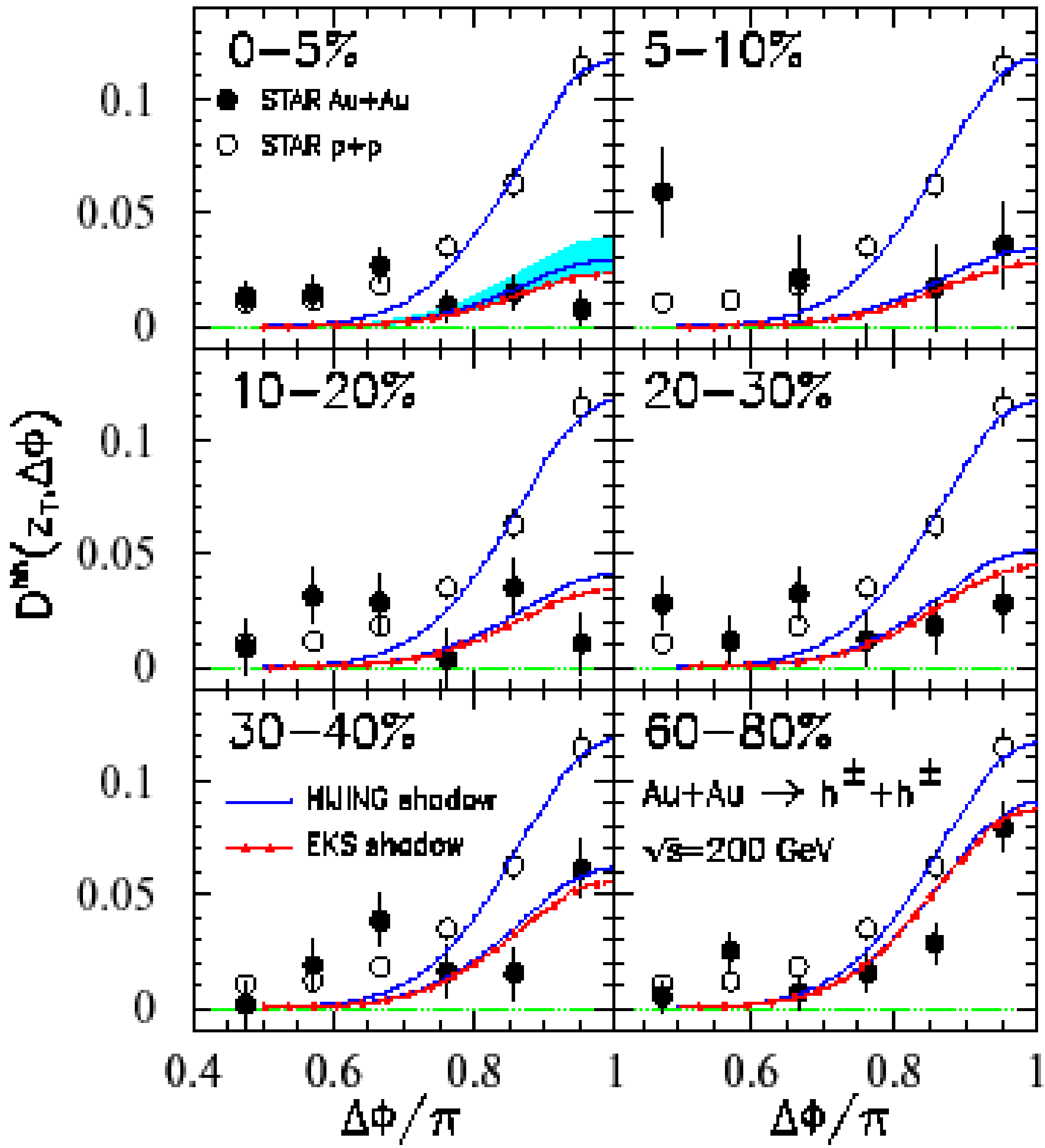
The dashed line corresponds to the $\langle|j_{Ty}|\rangle$ = 400 MeV/c

There is no significant broadening observed. Could be explained by jet fragmentation outside the QCD medium.



Back-to-back suppression in quenching theory

Quenching leaves always b2b from corona….



Summary

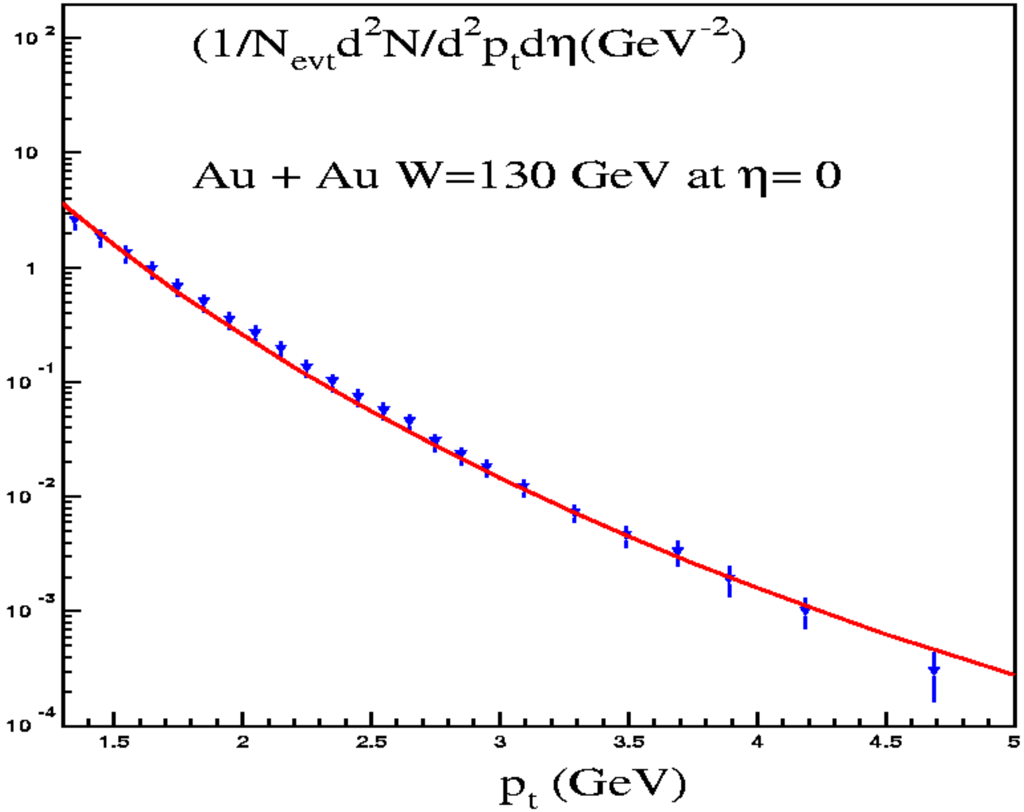
- HI physics enters the pQCD regime, but not exactly in the way we have (some of us) expected.
- First two years of RHIC running - unexpected experimental results in high-p_T sector, namely
  - huge high-p_T particles yield suppression
  - huge p_T and $\sqrt{s}$ independent azimuthal anisotropy
  - disappearance of back-to-back jet in central collisions
  - weaker back-to-back correlation observed at RHIC $\sqrt{s}$ = 200GeV relative to SPS $\sqrt{s}$ =17GeV
- No coherent picture yet, but we will find out soon !

Back up slides

Back up slides

Model III: High-pT suppresion

Dima Kharzeev hep-ph/0210332



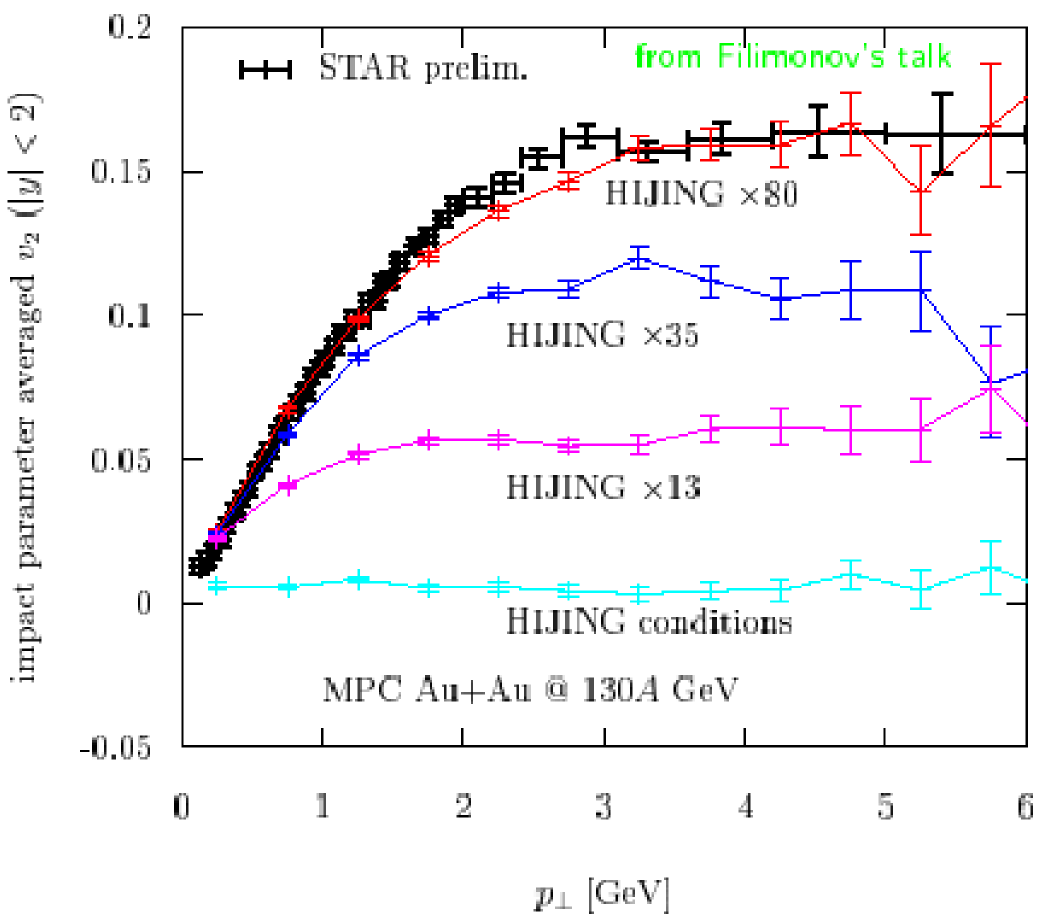
Looks good, but there is a lot of open questions. If CGC is right

- azimuthal anisotropy
- high-pt suppression

in pA should be significant.

<u>We will know in couple of days !!</u>

HIJING and opacity



- 80xmore opaque gluon plasma @ RHIC then from pQCD (see D. Molnar nucl-th/0005051, nucl-th/0104073 or

http://nt3.phys.columbia.edu/people/molnar)

Structure of the nucleon

Wavelength $\lambda = h/p$

AGS

SPS

RHIC

LHC

See the whole proton

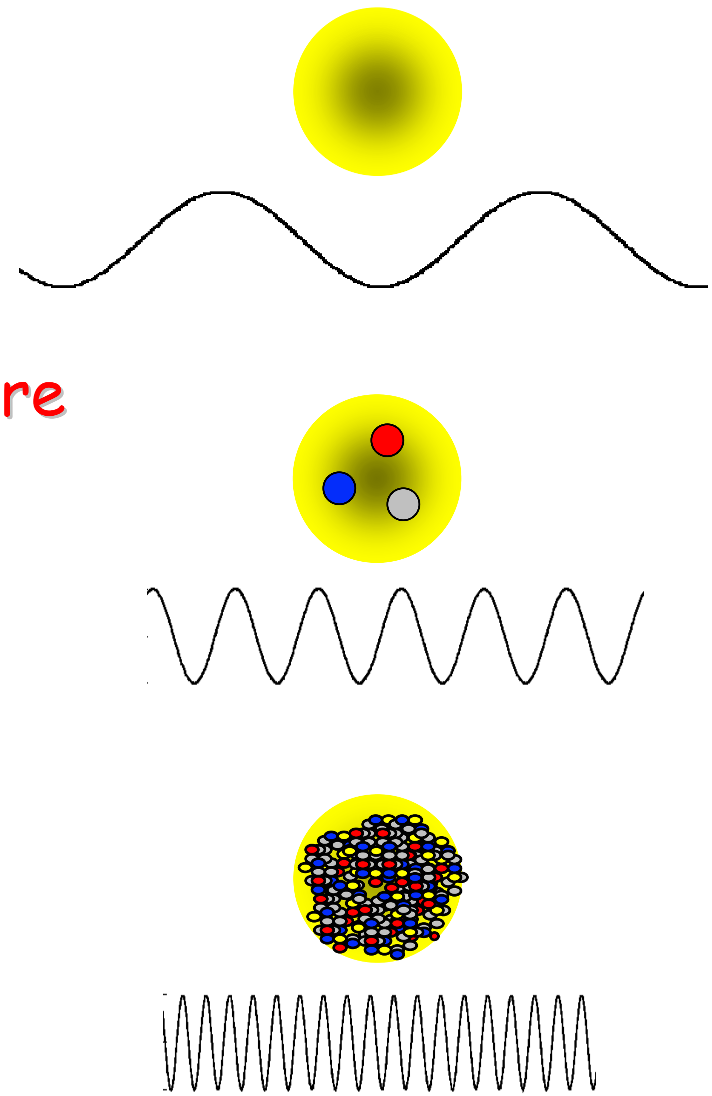
$Q^2 = 0.1\ GeV^2$

See the quark substructure

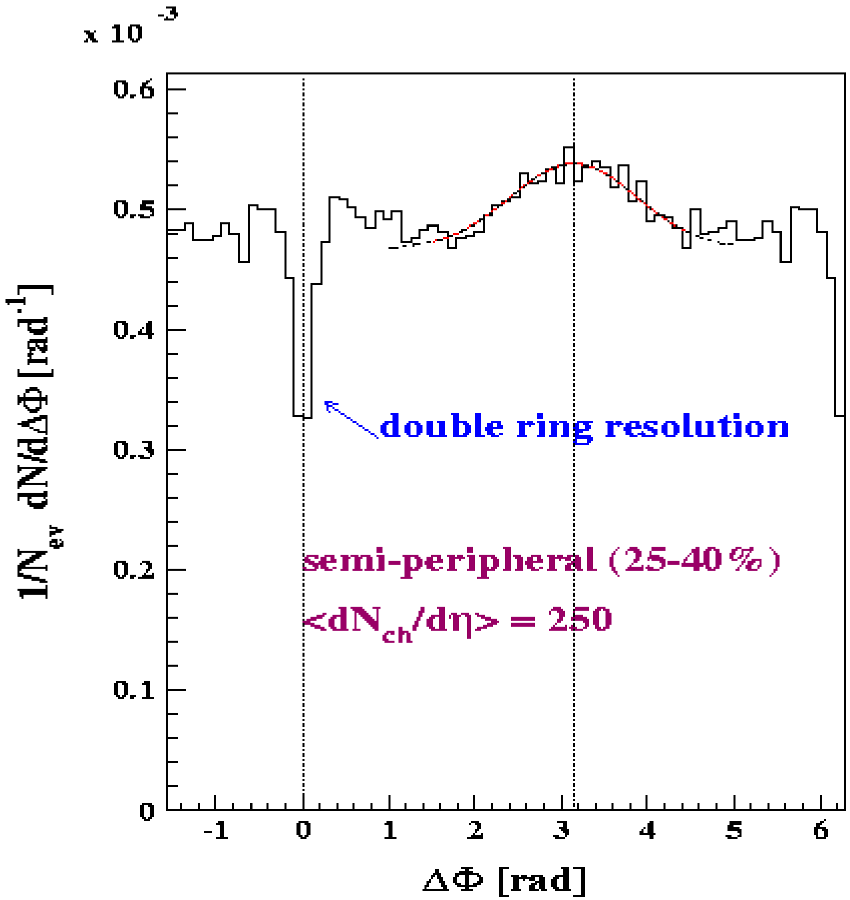
$Q^2 = 1.0\ GeV^2$

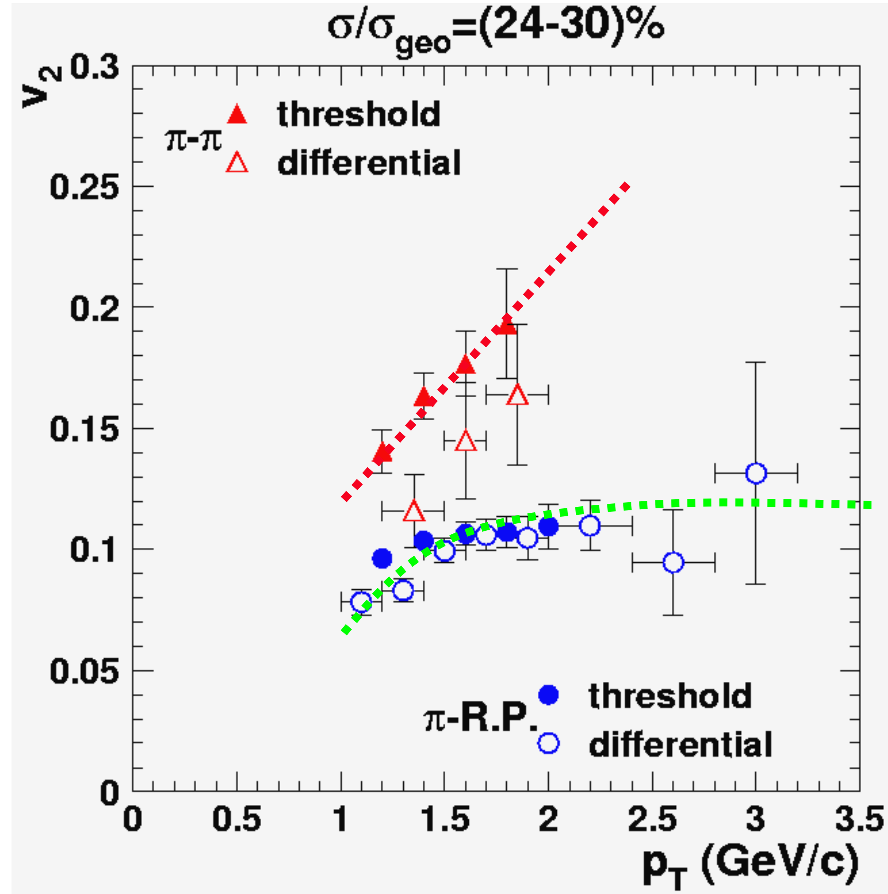
See many partons

$Q^2 = 20.0\ GeV^2$



CERES $\sqrt{s}$ =17GeV identified π^{+-} in RICH



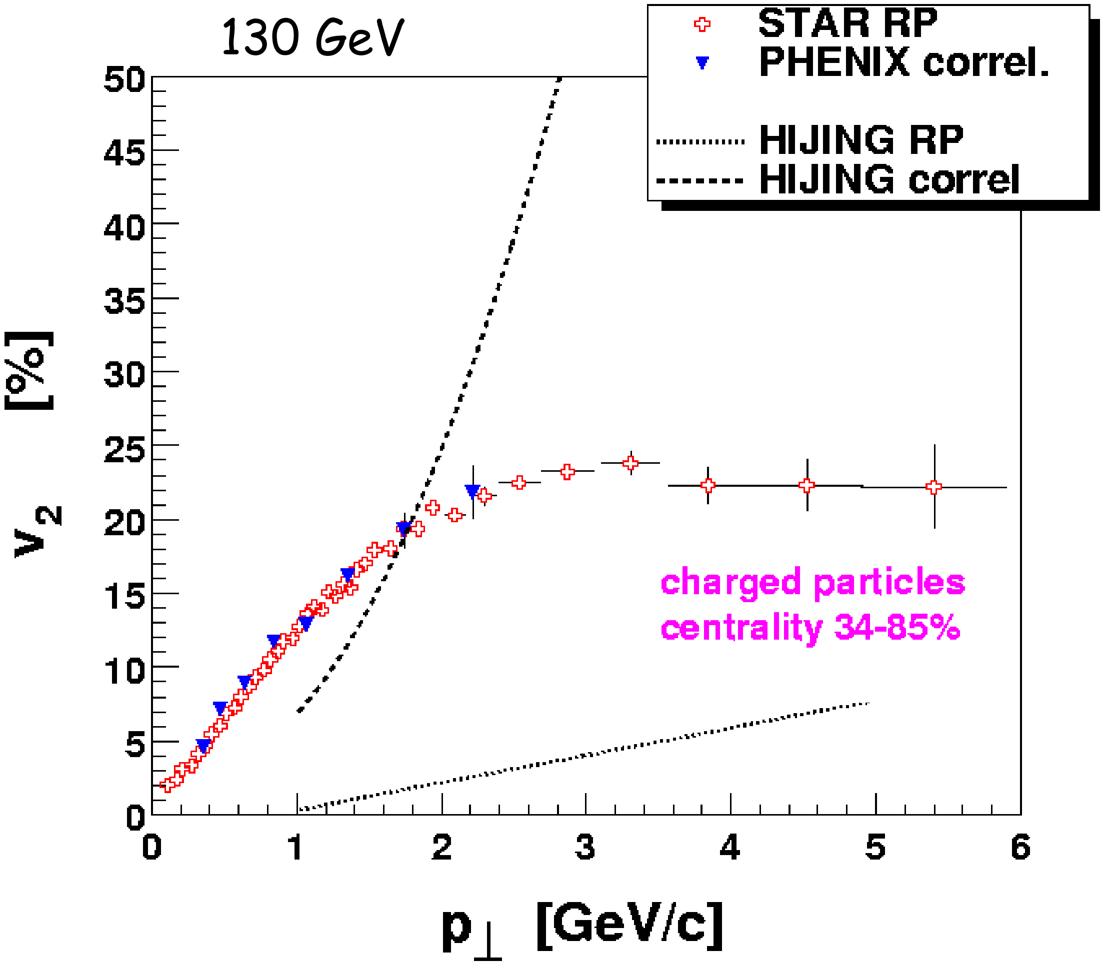


Large sample of high-pT pions identified in RICH (γ-threshold 32 -> pions > 5GeV/c)

Back-to-back part of correlation function was parameterized solely by v2(pT).

Significant excess of back-to-back correlations above 1.5-2GeV/c !

$v_2(p_\perp)$ PHENIX vs. STAR



Up to 2 Gev/c there is no or very little room for non-flow anisotropy !

- PHENIX two particle correl.
  - Good agreement with RP
- HIJING (dE/dz = 0 & 2 GeV/fm).
  - RP v_2 is too small over the full range, but grows with $p_\perp$,
  - Correlation v_2 is large, (not seen in data).

(See E.V. Shuryak, nucl-th/0112042)

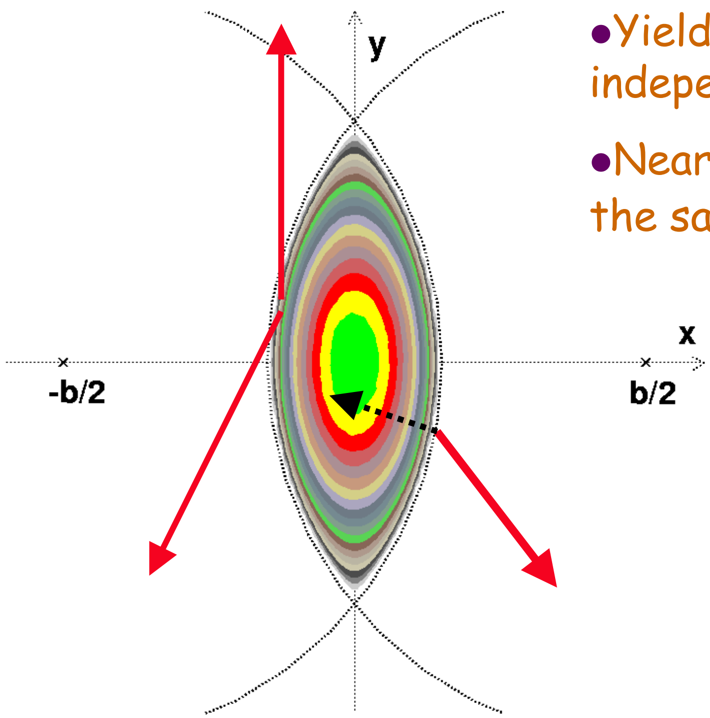
side remark:

$\langle x_\perp \rangle = 2 \langle p_\perp \rangle / \sqrt{s} \approx 0.1$ @SPS

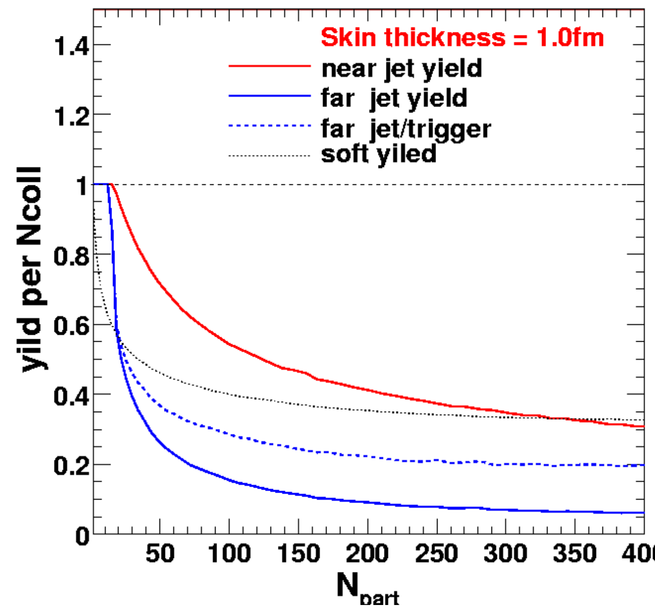
≈ 0.01 @RHIC

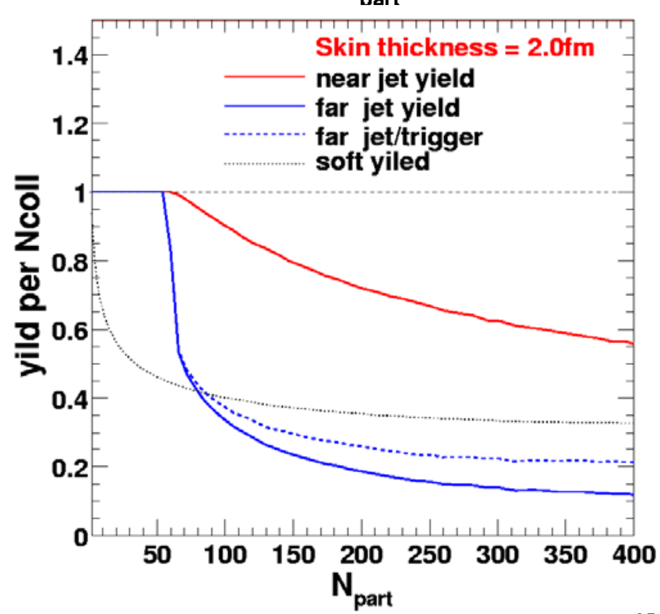
Surface Emission in Glauber Model

Radiation from thin surface slab towards outer half- plane.



- Yield per trigger independent on ΔR.
- Near/far suppressed in the same way.





$T_{AA}(b,rT)$ overlap function (hard sphere)->

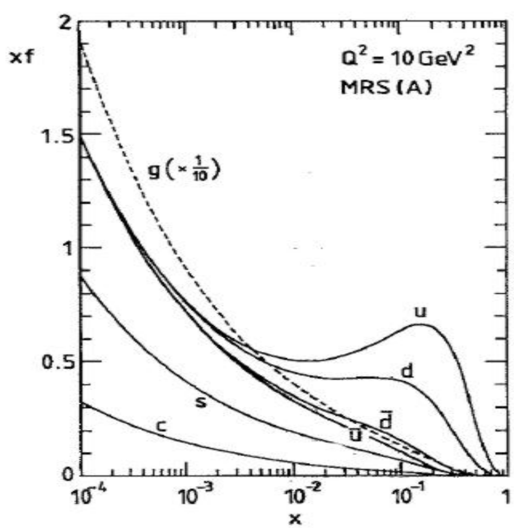
-> production prob. dist in (xT,yT)

pQCD ingredients

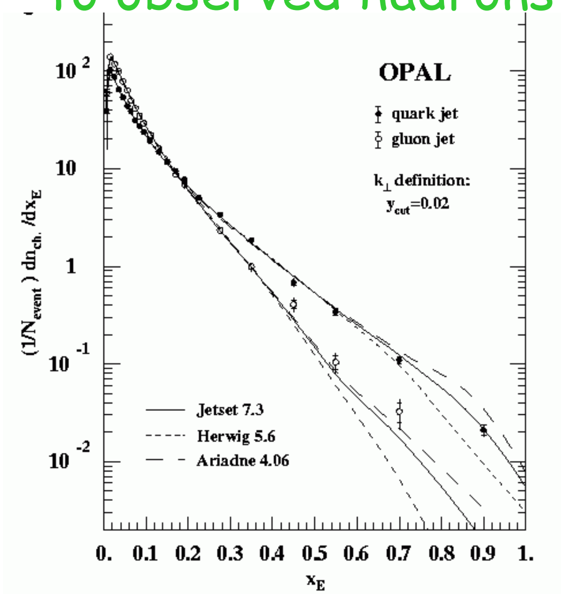
In order to calculate the yield of high p_T hadrons

$$E_h \frac{d\sigma_h^{pp}}{d^3p} = K \sum_{abcd} \int dz_c dx_a dx_b \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} f(\mathbf{k}_{Ta}) f(\mathbf{k}_{Tb}) \underline{f_{a/p}(x_a, Q_a^2) f_{b/p}(x_b, Q_b^2)}\ \underline{D_{h/c}(z_c, Q_c^2)} \frac{\hat{s}}{\pi z_c^2} \underline{\frac{d\sigma^{(ab\to cd)}}{d\hat{t}}} \delta(\hat{s}+\hat{u}+\hat{t})$$

Flux of incoming partons (structure functions) from Deep Inelastic Scattering



Fragmentation functions D(z) in order to relate jets to observed hadrons



Perturbative QCD

$$\sigma_{AA}(b_c) = \sigma_{pp} \int_0^{b_c} db^2 T_{AA}$$